FORAMINIFERAL PALAEOECOLOGY, SEDIMENTATION AND DIAGENESIS OF MIDDLE-UPPER JURASSIC SEDIMENTS OF KEERA HILL, KACHCHH, GUJARAT

ABSTRACT

THESIS

SUBMITTED FOR THE AWARD OF THE DEGREE OF

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IN

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BY

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DEPARTMENT OF GEOLOGY
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ABSTRACT

Jurassic rocks of Kachchh are globally famous for their varied and well preserved megainvertebrate fossils especially ammonites. These rocks have been the subject of extensive and intensive research since 1837 resulting in voluminous geological literature. However, most of the publications deal with megafossils and stratigraphy. Microfossils, especially foraminifera, though abundant and well preserved in these sediments, have not been paid due attention. Most of the micropalaeontological studies are devoted to systematics and interpretive studies involving palaeoecology, biostratigraphy, and palaeogeography are extremely rare. Moreover, detailed sedimentological investigations, including lithofacies, petrofacies [illegible] and diagenesis are [illegible].

In view of this, detailed foraminiferal and sedimentological investigations are undertaken in the present study with a view to interpret foraminiferal palaeoecology, provenance, depositional environment, and diagenesis of these rocks.

Jurassic rocks in the Kachchh region are exposed in three east-west trending parallel anticlinal ridges which are broken up into several isolated outcrops in the form of structural domes having quaquaversal dips. Most of the prominent domal outcrops are situated in the middle ridge. According to a well established and widely used classification, Jurassic rocks of Kachchh are grouped into Patcham, Chari and Katrol formations in ascending order.

A relatively small but well exposed domal outcrop of Jurassic rocks located in the middle ridge named Keera hill is selected for the purpose of the present study which is situated about 50 km northwest of Bhuj, the district headquarters of the Kachchh region. Only Chari and Katrol formations are exposed in the Keera hill. The Chari formation exposed in the Keera hill is divisible into nine lithounits and comprises mostly limestones and subordinate shales while the Katrol Formation comprises mainly sandstones. The Katrol Formation is devoid of foraminifera and, therefore, excluded from the foraminiferal investigation.

A total of 26 samples were collected form the Chari Formation exposed at Keera hill, mainly on the basis of lithological variation. Micropaleontological processing of the samples yielded 33 foraminiferal species which includes four species reported for the first time from the Kachchh region. The Keera hill foraminiferal assemblage is dominated by the family Vaginulinidae constituting 54.54% of the total fauna and includes eighteen species belonging to eight genera. The assemblage also contains some post-Jurassic species which bear characters of wind borne sediments and considered to have brought by wind from the nearby Palaeogene rocks and incorporated into Jurassic sediments. All the 33 foraminiferal species are described systematically and illustrated with the help of SEM photomicrographs.

The foraminiferal assemblage is used to interpret the palaeocology and depositional environment of the enclosing sediment employing some of the recent available methods for interpretations of foraminiferal palaeoecology, viz., Fisher index, test composition, morphogroups, and ecologically significant taxa. The foraminiferal assemblage indicated that the overall deposition of the Chari sequence exposed at Keera hill took place in shallow water, open marine environment confined to mid and outer shelf, having normal salinity and well oxygenated water. However, minor bathymetric fluctuations were detected during the deposition of the sequence which helped in dividing the sequence into ten palaeoecological units with water depth oscillating between mid to outer shelf. The fluctuations in palaeoecological conditions represents several minor transgressive and regressive phases during the deposition of the Chari sequence exposed at Keera hill, Kachchh and points towards tectonic instability of the depositional basin.

For sedimentological studies including textural, petrofacies and diagenetic studies, fifty-one samples of sandstones were collected from Katrol Formation in Keera hill from three different locations, the sandstones being hard, compact and yellowish brown colour. The studied sandstones are mainly fine and medium-grained, moderately sorted and moderately well sorted, near symmetrical and mesokurtic. Most of the grains are subangular to subrounded and show low sphericity.

The studied sandstones, consisting of abundant quartz followed by feldspars, rock fragments, mica and heavy minerals, suggest that the source rocks for Katrol sandstones include granites, granite-gneisses, low and high grade metamorphic rocks and some basic rocks. These rocks most probably got eroded and weathered from parts of Aravalli and Delhi Folded Belt. Their palaeo-current pattern studied by Balagopal and Srivastava (1975) suggests that the provenance of Katrol sandstone was located in the south, which was in all probability south-west extension of Aravalli Delhi Folded Belt (ADFB), now covered partly below the post-Jurassic rocks of Kathiawar and partly under the Arabian Sea. The tectonic style of Aravalli- Delhi folded belt makes a collage of recycled orogen and basement uplift provenance.

For compositional field characteristic of different provenance, five triangular diagrams were employed, i.e., QtFL, QmFLt, QmPK (Dickinson, 1985) and QpLvmLsm, LmLvLs (Ingersoll and Suczek 1979; Suczek and Ingersoll, 1985) for present study. But most of the samples fall in the continental block provenance. In addition to this, the QpLvmLsm and LmLvLs diagrams indicate sediment were contributed from rifted continental margin, suture belt and mixed magmatic arc and subduction complex. This is in accordance with ADFB tectonic evolution and mode of origin of Kachchh Basin. False signature of continental block provenance may be the result of several factors, which have modified the original composition of the detritus in one way or the other. The major controls on the detritus composition are exerted by palaeo-climate, transport, sediment recycling and diagenesis.

The Katrol Sandstones of the Keera hill show dominance of floating grains followed by point, long and concavo-convex contact, sutured contact grains being least common. Their contact index values averages 1.45. The high percentages of floating grains, point contacts and low value of contact index indicate that the sandstones were subjected to little compaction and pressure-solution as a result of either shallow burial or early stage cementation. The high minus-cement porosity suggests early stage cementation. The presence of long contact suggests that the compaction of sandstone took place in early stages, when grains rotated and adjusted themselves to the boundaries of the adjacent grains. The low proportion of concavo-convex and sutured contact indicates limited grain dissolution due to chemical compaction.

In the studied sandstones, six types of cement have been identified and described including calcite, iron oxide, silica, dolomite, clay and matrix in order of abundance. Matrix is in the form of silt and clay. Calcite cement is present in all the samples and occupies intergranular pore spaces. The calcite cement occurs in two forms--microcrystalline calcite (micrite) an sparry calcite. The microcrystalline calcite cements are present in a few samples as pervasive pore filling. The sparry calcite, probably a late stage cement, shows both pervasive and patchy distribution. The larger sized crystals of calcite indicate slower rate of precipitation from dilute solutions rather than rapid crystallization (Dapples, 1971). The precipitation of microcrystalline calcite cement probably took place at shallow depths as evidenced by open framework and entrapped non-strained clay matrix. Later, during burial diagenesis, microcrystalline calcite cements were replaced by sparry calcite in meteoric hydrologic regime along the interface of zone of aeration and saturation. The presence of oversized pore-filled calcite cement might be due to destruction and leaching of labile framework grain, possibly feldspar, which may have taken place at sediment-water interface. Iron oxide cements are present in three different forms (i) as pervasive pore filling which is most common (ii) as occasional patches and (iii) as thin coating around detrital grain boundary which is the least abundant. The silica cement occurs in small amount, generally in the form of quartz overgrowth, which shows optical continuity with detrital quartz grains. The overgrowth develops by direct precipitation of silica from aqueous solution and grows into the intergranular spaces. The presence of small amount of silica cement can be attributed to limited compaction of sandstone, thereby causing very little pressure solution, which is the most important indigenous source of silica. But other source could be descending meteoric water saturated with silica. Dolomite occurs as of isolated crystals, in patches and as pervasive which forms rhombic crystals, in general, is found to replace calcite. It has brown stains and is probably 'ferroan'. The dolomite rhombs are euhedral to subhedral and abut against framework grains. Such rhombs also exhibit sharply defined zoning with iron-rich and iron-poor composition alternating. The clay cement is present in minor amount mainly Kaolinte and occurs as intergranular microcrystalline aggregate of both allogenic and authigen[illegible] Matrix in form of detrital silt and chert mixed with fine grained musc[illegible]y are present in varying amount. Most of the matrix material is sy[illegible]al, and hence pore-filling. Matrix exerts influence on diagenetic pro[illegible]y supplying chemical entities and bulk properties, such as porosity and pe[illegible]ility by pore occlusion. The very low amount of matrix seen, probably, decanted from infiltrating muddy pore water.

The sandstones with pervasive cement of calcite and iron-oxide show sign of development of secondary porosity involving dissolution and leaching. Most sandstones have low primary porosity due to pores profusely cemented with calcite and iron oxide, indicative of very early stage cementation. The oversize pores filled with cement are also observed to be coated by iron-stain. The high percentage of MCP (average 33.3%) indicates open framework which suggests that sandstones were probably cemented soon after deposition before significant burial or low mechanical compaction ensued. The depth of burial of Katrol Sandstone is from 705.64m to 1758.62m (average 1017.12m). Therefore, compaction seems to be a secondary factor in the porosity reduction. The overall porosity loss due to compaction averages at 17.57% and due to cementation 21.92%.

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14th July, 2010

CERTIFICATE

This is to certify that **Mr. Mohd. Haris Azim Khan** has completed his research under our supervision for the degree of Doctor of Philosophy of the Aligarh Muslim University. This work is an original contribution to our knowledge of the Foraminifera and Sedimentology from the Jurassic of Kachchh and has not been published anywhere either in part or in full.

He is allowed to submit the work for the Ph.D. degree of the Aligarh Muslim University, Aligarh.

A. H. M. Ahmad

Dr. A.H.M. Ahmad
(Co-Supervisor)

Dr. Abu Talib
(Supervisor)

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(MOHD. HARIS AZIM KHAN)

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CHAPTER 1

INTRODUCTION

PURPOSE OF STUDY

The marine Jurassic rocks of Kachchh deposited in an extension of Tethys at the northwestern corner of the Indian Plate, are particularly well-known for their megafossils. These rocks first received the attention of geologists and palaeontologists when this region was hit by major earthquake in the year 1819. Since then, a large amount of work has been carried out on stratigraphy and megafossil of these rocks. The disastrous earthquake on 26 Jan. 2001 which rocked the entire Kachchh has once again attracted the attention of geologists to this region.

Although Jurassic rocks of Kachchh have been subjected to intensive stratigraphical and palaeontological studies since 1937, relatively little attention has been paid to sedimentological and micropalaeontological investigations of these sediments.

Tewari (1957) was the first to report foraminifera from Jurassic rocks of Kutch but the first detailed study was carried out by Subbotine et al. (1960). This was followed by a number of publications on Jurassic foraminifera of Kachchh. Of these, publications by Bhalla and Abbas (1978), Bhalla and Talib (1991), Pandey and Dave (1993), and Gaur and Talib (2009) are the only detailed studies on Jurassic foraminifera of this region. However, these publications deal mainly with systematics and foraminiferal biostratigraphy. No serious attempt has been made to interpret palaeoecology and depositional environment of these sediments using mircofossils.

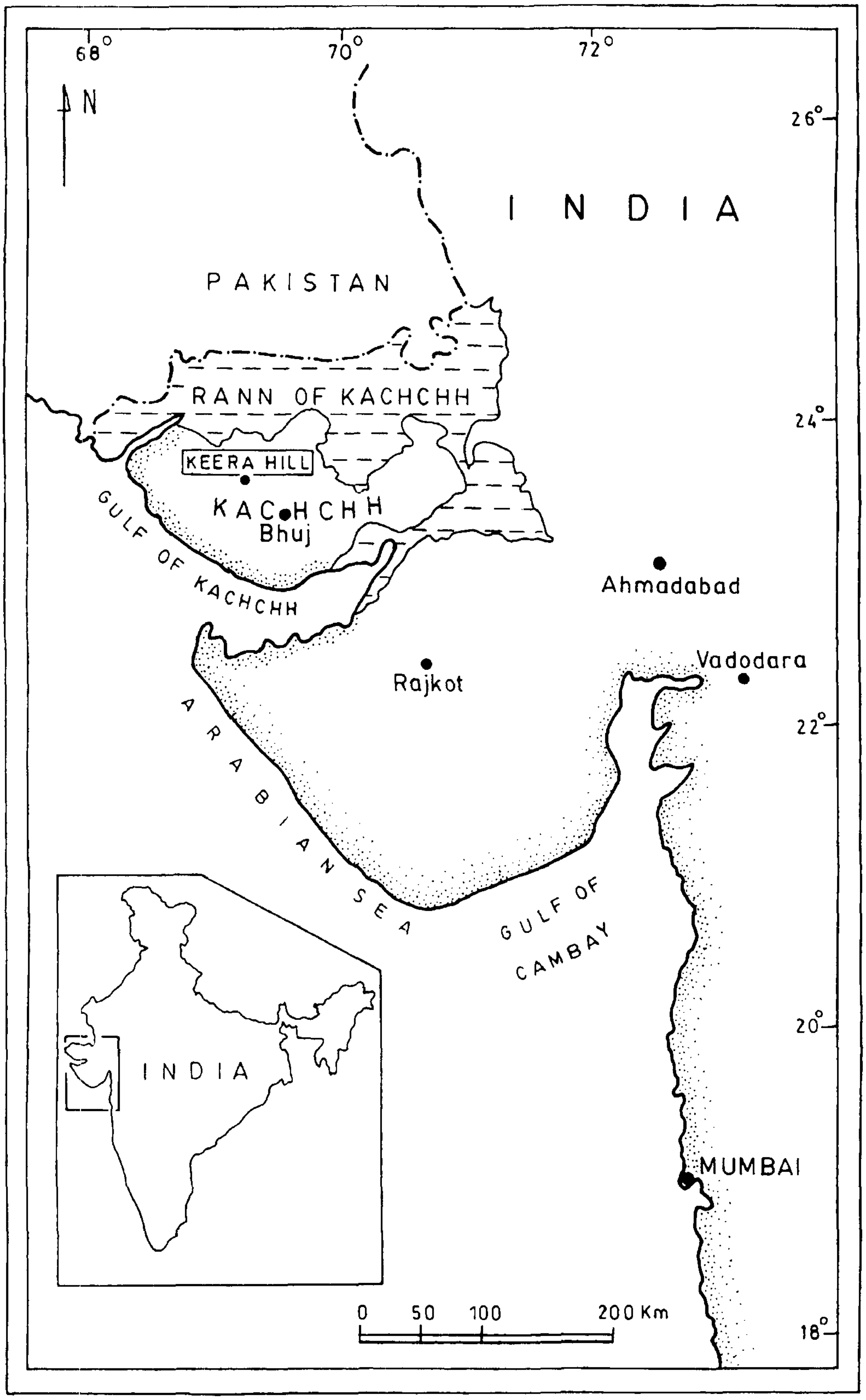


Figure 1: Location map of Kachchh

A study of literature reveled that little work has been done on sedimentological aspects of the Kachchh Jurassics including depositional environment, basin geometry, palaeoclimate and depositional history of the basin (Biswas, 1981; Deshpande and Merh, 1980; Dubey and Chatterjee, 1997, 1999). Few publications are available on petrofacies and diagenesis of these sediments (Ahmad *et al.*, 2000, 2006 , 2008). As Kachchh basin has been classified as 'Category II type' of basin by the Oil and Natural Gas Corporation Ltd. of India where hydrocarbon occurrences have been found, it needs exhaustive sedimentological database.

In view of the great development of Jurassic rock of Kachchh region, extensive sedimentological and micropalaeontological studies are required in order to compose a vivid picture of their depositional environment, tectonic setting and diagenesis of these rocks.

In view of the foregoing, a comprehensive sedimentological and foraminiferal study of Jurassic rock of Kachchh has been undertaken in the present study. The present work concerns a small but well-exposed area of these rocks in Keera Hill near Motichur village, about 70 km from northwest of Bhuj (Figure 1).

LOCATION AND ENVIRONS OF THE AREA

The study area is located in Keera Hill about 70 km north-west of Bhuj, headquarter of district Kachchh which is bounded by little Rann in the east, Arabian Sea in the west, Gulf of Kachchh in the south and the Great Rann in the north. The Kachchh region presents a flat undulating topography with river beds, well-tilted valleys, small hillocks and isolated peaks. The major part of the region is a desert which is either alluvial or partly fluvio-marine or wind blown with saline wastes in Rann of Kachchh (Figure 2).

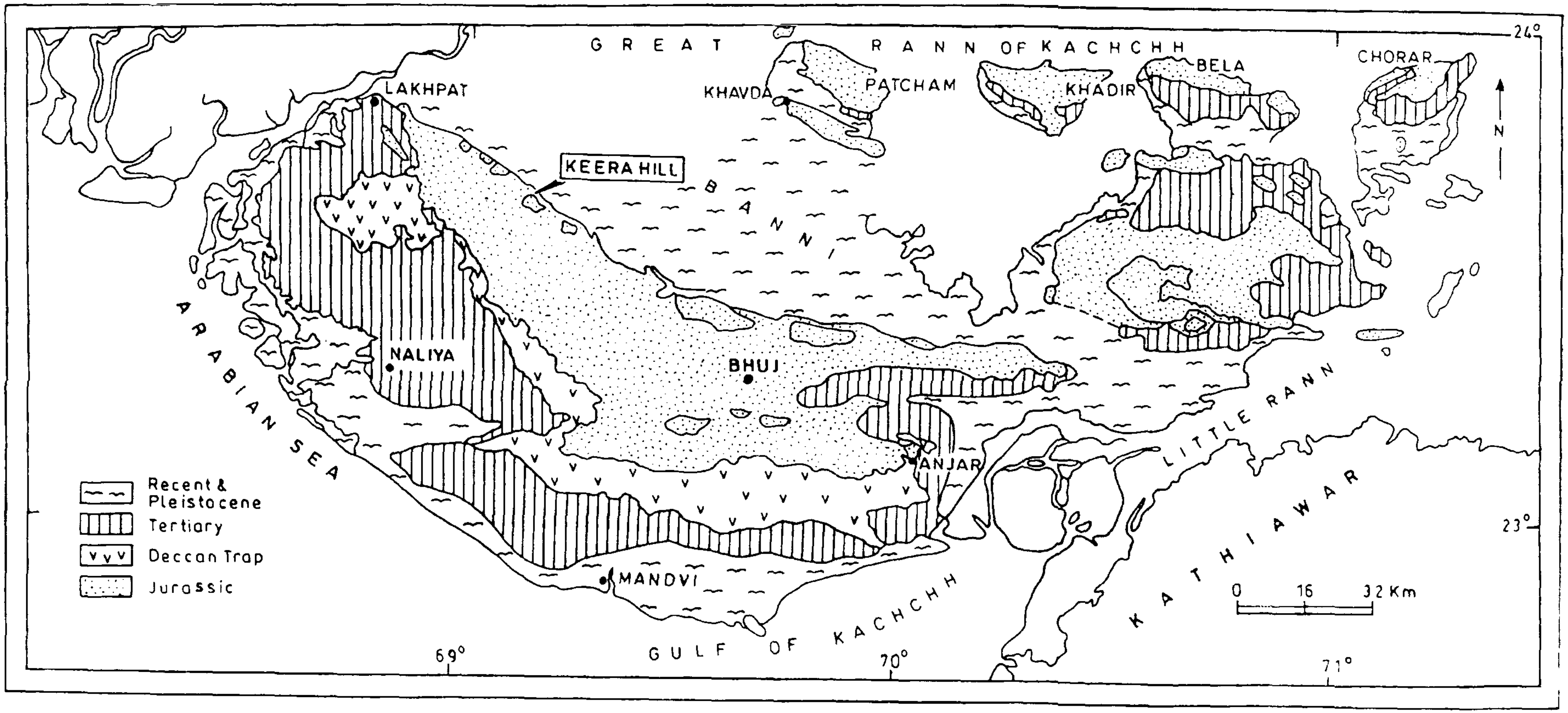


Figure 2: Geological map of Kachchh

Keera Hill is a domal outcrop lying between latitudes 23°31' and 23°33' and longitudes 69°12' and 69°16'. The entire hill is dissected by a number of small *nalas* (small seasonal dry streams), bearing water only in rainy season. A well-developed section exposed along a *nala*-cutting (23°33'30" : 69°15'30") is selected in the southeastern flank of Keera Hill for the foraminiferal and microfacies studies. This originates near the centre of the hill and vanishes in Banni plain. For texture, detrital mineralogy, petrofacies and diagenetic studies of sediments three well exposed locations were selected in the south, north and southwest flanks of Keera Hill.

Keera Hill is situated near Motichur village which lies under the Nakhatrana Taluka of Kachchh district. The village Motichur is connected with Bhuj by mottled motorable road via Nakhatrana town and few daily bus services are available. The city of Bhuj is connected by air to Delhi and Mumbai, and by road and railways to Palanpur and Ahmedabad.

METHOD OF STUDY

Field Method

It includes field investigations and collection of samples. For foraminiferal study, bed to bed samples were collected along the well exposed section in *nala*-cutting located in the southeastern flank of Keera Hill. The samples were collected on the basis of lithological variations. The rock types encountered in this section during sample collection are mainly limestones with subordinate shales.

For texture, detrital mineralogy, petrofacies and diagenetic study, three well exposed vertical stratigraphic sections were measured and bed to bed samples of sandstones collected depending upon the thickness of the exposed clastics and any apparent visible change in lithology. Samples were taken from half to one meter interval.

LABORATORY PROCEDURE AND TECHNIQUES

For foraminiferal study, sample collected during field work were prepared by crushing and boiling them with sodium carbonate. The disintegrated materials were washed and screened through a set of standard sieves. The washed and sieved material was dried in oven. The dried material was then placed on a picking trey and foraminiferal tests were picked with the help of a fine sable hair brush under stereozoom binocular microscope. Some of the specimens were treated in an ultrasonic vibrator for further cleaning. The foraminiferal specimens were then arranged in squared microfaunal slides for identification and study. All the microphotographs of foraminifera for plates were prepared with the help of Scanning Electron Microscope (SEM), Modal No. PSEM 515, Philips, Holland at Wadia Institute of Himalayan Geology, Dehradun, India.

The texture, detrital mineralogy, petrofacies and diagenetic studies are based on examination of thin sections. The textural attributes of sandstone comprises grain size analysis, roundness and sphericity, based on thin section study of fifty-one sandstone samples. Grain size analysis was carried out by measuring the long axis of 250 to 300 points from each thin section, counted with the help of ocular micrometer in eyepiece and point counting mechanical stage as described by Chayas (1949). Roundness and sphericity were also analyzed with thin section and comparator chart given by Power (1953). The detrital modes of sandstone were evaluated by counting 300 to 400 points from each thin section of sixty-one sandstone samples according to the 'Gazzi-Dickinson method' adopted by Zuffa (1980), and Ingersoll et al. (1984). The terminology proposed by Folk (1980) was employed for identifying and describing the detrital grains of studied sandstone. The petrofacies were recalculated to 100 percent following the method developed by Ingersoll and Suczek (1979) and Dickinson (1985). For diagenetic studies of sandstone, thin section of fifty-one samples were employed by counting 250 to 300 points at grid point spacing to identify authigenic phases and estimating compactional parameters.

Apart from this, detailed analytical methods are described separately in the chapters.

REPOSITORY OF THE MATERIAL

All the described and illustrated specimens of foraminifera have been housed in Micropalaeontology Laboratory of the Geology Department, Aligarh Muslim University, Aligarh and are prefixed with AMUGD, Cat. No MF. 504-536. The thin sections of limestones and sandstones are housed in the Sedimentological Laboratory of the Geology Department, Aligarh Muslim University, Aligarh.

CHAPTER 2

PREVIOUS INVESTIGATION

Kachchh basin, situated at the western margin of the Indian plate, is considered as one of the most important Jurassic localities of the Indo-East African marine faunal province, and is globally famed for its rich and stratigraphycally significant ammonoids. This region has fascinated geologists and palaeonlogists since the middle of the nineteenth century for its abundant fossils, well exposed sedimentary sequence, and mineral deposits.

The maximum amount of work has been done on megafossils from Jurassic rocks of Kachchh, especially ammonoids. Among the microfossils, some work has been done on foraminifera and ostracods. On the other hand, little attention has been paid on sedimentological aspects of Jurassic rocks of Kachchh including microfacies, petrofacies and diagenetic evolution of these rocks. It is beyond the scope of the present study to review the work done by earlier workers in different branches of Geology on this area. Only those references which concern only foraminifera, microfacies, petrofacies and diagenesis of the Jurassic sediments of Kachchh have been mentioned in detail.

Tewari (1957) reported benthic foraminifera – *Aulotortus* from the Patchum series of Habo hill, central Kachchh and also recorded *Textularia, Bigenerina, Spiroplectammina* and *Gaudryina* from these rocks.

Subbotina *et al.* (1960) described and illustrated thirty five species of foraminifera from southeast of Lodai village on the eastern flank of Habo hill, Khawda (in Rann of Kachchh) and also from Jurassic exposures of Rajasthan. These authors also observed that out of thirty five foraminiferal species twelve were new. These foraminiferal assemblages were recorded from Chari 'series' of Kachchh and Jaisalmer Formation of Rajasthan and suggested an age ranging from Callovian to Oxfordian.

Agrawal and Singh (1961) recorded the following genera of foraminifera from near Habo hill: *Rhabdammina, Ammodiscus, Ammobaculites, Quinqueloculina, Triloculina, Robulus, Lenticulina, Nodosaria, Saracenaria, Vaginulina, Palmula, Nonion, Elphidium, Rotalia* and *Anomalina*. These authors (Agrawal and Singh, 1961) pointed out that the presence of *Elphidium*, essentially a Tertiary genus, is unusual in the Jurassic rocks but they did not give any explanation for this anomaly.

Balgopal and Srivastava (1975) studied the palaeocurrent and provenance of Jurassic rocks of central Kachchh around the city of Bhuj between the north latitudes of $23^0 11'$ and $23^0 28'$ and east longitudes of $69^0 32'$ and $69^0 56'$. Their study was based on petrography, heavy mineral and palaeocurrent pattern of the various rock units of Chari, Katrol and Bhuj formations. The petrography and heavy mineral content were utilized in deciphering the probable composition of the provenance with respect to the study area. The location of the source area was deciphered by means of palaeocurrent study using various primary sedimentary structures, such as cross bedding, parting lineation and ripple marks.

On the basis of their study, they found that the Chari Formation had received the detritus from north of the study area which consisted of low to medium grade metamorphic rocks, acidic igneous rocks, pegmatites and some basic rocks. According to these authors (*op. cit.*) the Precambrian schists, granites and associated pegmatites and basic rocks that today lie buried under the Great Thar Desert, constituted the provenance for the clastic sediments of Chari Formation. These authors also observed that the Katrol sediments received the detritus from the south consisting of medium to high-grade metamorphic rocks. It is most likely that the Katrol provenance lay along the southwest extension of the belt of Aravalli and Delhi rocks, now covered partly below the post Jurassic rocks in Kathiawar and partly under the Arabian Sea. The Aravalli Group of rocks now underlying the northern Gujarat plains in the east were the parent rocks for Bhuj Formation.

Bhalla and Abbas (1975a,b,c; 1976a,b; 1978; 1984) carried out detailed study on foraminiferal systematics, depositional environment and stratigraphy of Jurassic sediments exposed at Habo hill, Kachchh and published a series of papers. Bhalla and Abbas (1975a; 1976a) reported sixty-five species of foraminifera. The foraminiferal assemblage being dominated by family Nodosariidae which is represented by forty species. Out of the total species, ten were new and some were indeterminate species which were recorded for the first time from Jurassic of Kachchh. Bhalla and Abbas (1975b) described and illustrated variation in *Lenticulina subalata* (Reuss) and concluded that this species like other Jurassic Nodosariids, exhibits a wide range of variation and caution must be taken while dealing with taxonomy of nodosariids. Bhalla and Abbas (1975c) also reported the post-Jurassic elements in Jurassic foraminiferal assemblage of Habo hill. This includes thirteen genera represented by a small number of specimens with obliterated morphological features, frosted surface and well rounded shapes. On the other hand, the Jurassic foraminifera were abundant, well preserved and show clear morphological features without any strain on their shape and abrasion of their surface. These authors (Bhalla and Abbas, 1975c) suggested the following reason for the presence of the Post-Jurassic elements in the Jurassic foraminiferal assemblages of Habo hill, Kachchh: as Kachchh basin is bounded by beaches on the western and southern margins and marine Tertiary rocks are well exposed in its northwestern part. It is most likely that during summer months when strong westerly winds and dust storms prevail in this arid region, the post-Jurassic foraminifera along with other material were blown from western and northwestern parts of Kachchh and sprayed over the Jurassic exposures present in the eastern sector. Thereafter, they impregnated the Jurassic sediments through percolating water during rainy season and got entombed in the sediments as 'leaked' material. Bhalla and Abbas (1976a, 1984) discussed the palaeoecology of these sediments by dividing the entire sequence of Habo hill into five palaeoecological unit and suggested the overall deposition of Kachchh Jurassic took place in a near-shore, shallow water, tectonically unstable marine basin which fluctuated considerably between lagoonal, neritic and littoral environment from time to time. Bhalla and Abbas (1976a) suggested a Callovian to Oxfordian age for the studied section of Habo hill and stated that the Jurassic foraminiferal assemblages of Kachchh compares well with the Jurassic foraminiferal assemblages of Rajasthan, Iran, Egypt, Afghanistan and Somalia, showing Tethyan affinities. On this basis, these authors supported the view that during Middle and Upper Jurassic times, the entire Rajasthan and Kachchh region were covered by a gulf of the Tethys which emerged from near Iran and after covering Afghanistan, Baluchistan and east coast of Africa extended to Madagascar. Bhalla and Abbas (1978) finally published a detailed illustrated account of the Jurassic foraminifera of Habo hill, Kachchh giving a systematic account of sixty five species. The studied section of Habo hill comprises Patcham, Chari and Katrol 'series'. The first two 'series' contain rich foraminiferal assemblages and third one is barren of indigenous foraminifera of Jurassic age.

Shringarpure and Desai (1975) reported nineteen species of foraminifera belonging to family Nodosariidae from Manfara dome section of Wagad hill block, Kachchh.

Shringarpure *et al.* (1976) revealed an interesting phenomenon of faunal mixing in the Mesozoic stratigraphic sequence exposed in the western Wagad region of the eastern Kachchh. They observed that the foraminiferal assemblages are mixed with minor amount of ostracoda, bryozoa and echinoderm spines, along with microscopic plant tissues and insect skeletons of Tertiary, sub-Recent and Recent age, associated with older mesozoic sediments of Jurassic and Cretaceous periods. These authors (*op. cit.*) suggested that natural agencies like storm wave, stream current, wind action, ice rafting or even the activities of birds were responsible for this mixing. They also observed that robust foraminiferal genera of *Ammonia, Nonion, Quinqueloculina, Elphidium, Discorbis, Cibicides* etc. have undergone two previous depositional cycles before reaching their present depositional site.

Singh (1977) described and illustrated five species of genus *Epistomina* from the subsurface sequence at Banni, Rann of Kachchh. He proposed two biostratigraphic assemblage zones, *Epistomina stellicostata - E. alveolata* Assemblage-zone and *E. ventriosa–E. mosquensis* Assemblage -zone and suggested a Late-Jurassic age for the subsurface rocks.

In extension of his previous study, Singh (1979) proposed seven biostratigraphic zones for the subsurface Jurassic sequence of Banni, Rann of Kachchh, on the basis foraminifera, *Charites* spp., and ostracoda. These seven zones are as follows: Barren zone, *Charites-Otocythere* Assemblage-zone, *Lenticulina dilectaformis–L. carinocordatus* Assemblage-zone, *Epistomina stellicostata–E. alveolata* Assemblage-zone, *Eoguttulina liassica–Vaginulina cryptospira* Assemblage-zone, *Lenticulina–Nodosaria* Assemblage-zone, *Epistomina ventriosa – E. mosquensis* Assemblage-zone and *Lenticulina* zone. He also suggested that the beds of *Charites-Otocythere* Assemblage-zone were deposited in a brackish to marine environment whereas rest of the sequence was deposited in an inner-neritic environment.

Bhall and Talib (1978; 1980) reported nineteen foraminiferal species from a section of Chari 'series' near Badi village, central Kachchh. On the basis of foraminiferal assemblages combined with field observations, it was suggested that the overall deposition of Chari sequence near Badi was accomplished in a near-shore, shallow-water, marine environment which fluctuated between littoral to infraneritic conditions. These authors also assigned a Callovian-Oxfordian age to the studied sequence on the basis of foraminiferal assemblage. The Badi foraminiferal assemblage shows close affinities with those described from other regions of the Tethyan realm and supported the contention that during the Middle and Late Jurassic time, a gulf stretched from Tethys in the north to Madagascar in the south, which also covered the Kachchh region.

Deshpande and Merh (1980) proposed a sedimentary modal of Wagad hill in the eastern part of Kachchh, western India; comprising environment of deposition, basin geometry, lithic fill, lithic arrangement, directional structures and tectonic setting. The rocks exposed in studied area range in age from Middle Jurassic to Lower Cretaceous and are encircled by a thin and narrow fringe of Tertiary sediments. These authors suggested that the area experienced a prograding delta system with gradual shift of stand line from east to west during the course of deposition.

Bhalla and Lal (1985) reported seventeen species of Jurassic foraminifera from Chari sequence, exposed in the northern flank of Kaiya hill, Kachchh. On the basis of filed and foraminiferal investigations, these authors suggested that the overall deposition of Chari sediments at Kaiya hill took place most probably in a near shore, shallow water, marine environment. The presence of *Citharina hetropleura, Dentalina guembeli* and *Patellinella poddari* indicates a Callovian to Oxfordian age for the studied section.

Bhalla and Talib (1985a, b, c; 1991) published a number of papers on the foraminiferal systematics, biostratigraphy and depositional environment of the Jurassic Sediments exposed at Jhurio hill, Kachchh. Bhalla and Talib (1985b, c) reported fifty-three species of Jurassic foraminifera from the Jhurio hill, Kachchh. Of these, only two were new and majority of them were described for the first time from the Indian region. The foraminiferal assemblage was dominated by the family Nodosariidae. The foraminiferal assemblage also included nine post-Jurassic foraminiferal species. The post-Jurassic foraminifera show sign of wind borne sediments and appear to have been brought in from the Tertiary sediments and Recent beach sands exposed in nearby western areas by strong westerly winds prevailing during summer months in the region and then getting entombed in the Jurassic sediments through percolating rain water during monsoon season. These authors (Bhalla and Talib, 1985c) suggested the depositional environment of the Jurassic sediments exposed at Jhurio hill, Kachchh, on the basis of foraminiferal assemblages combine with field observation and concluded that these sediments were deposited in a near-shore, shallow water, marine basin which was tectonically rather unstable as evidenced by occasional shifting of the shoreline. The present Jurassic foraminiferal assemblage exhibits close affinity with Jurassic assemblages from other regions belonging to Tethyan Realm, *viz.*, Afghanistan, Iran, Egypt and Somalia. These authors also assigned a Callovian to Oxfordian age to the studied sequence on the basis of foraminiferal evidence and demarcated, Callovian-Oxfordian boundary. Bhalla and Talib (1985a) carried out detailed variation study in *Lenticulina quenstedti* (Guembel) and concluded that this species like other Jurassic nodosariids, exhibit a wide range of variation in its morphology and commented that precaution must be taken while dealing with taxonomy of Jurassic nodosariids. In view of their previous study, Bhalla and Talib (1991) presented a detailed systematic account and illustrated the foraminiferal assemblage of the Jurassic sediments exposed at Jhurio hill, Kachchh.

Govindan *et al.* (1988) described and illustrated benthic foraminiferal species belonging to Epistominids, Lenticulinids and agglutinated genus *Dorothia* across the Jurassic-Cretaceous boundary, from wells drilled in Kutch Mainland. These authors (Govindan *et al.*, 1988) marked the Early Cretaceous-Late Jurassic boundary between the extinction level of *Epistomina caracolla* and *Epistomina stelliscotata*. These authors (Govindan *et al.,* 1988) divided the entire sequence into six assemblage zones on the basis of highest occurrence level of zonal markers.

Bhalla and Gaur (1989) erected a new vaginulinid species from the Jurassic (Callovian) sediments of Jumara hill, central Kutch. The new species was designated as *Marginulina jumaraensis* and these authors (Bhalla and Gaur, 1989) inferred that it thrived in a wide range of environmental conditions from shallow, open marine to paralic, such as marsh or lagoon.

Mandwal and Singh (1989) described and illustrated thirteen index benthic foraminiferal species of genera *Garantella, Epistomina, Pseudomarssonella, Riyadhella, Singhamina* and *Tandonina*, for the first time from the Patcham – Chari sediments exposed in Jhurio hill, Kachchh. On the basis of these species, the authors (Mandwal and Singh, 1989) suggested a Bathonian age to the sequence exposed in the lower part of Jhurio hill and also demarcated Bathonian – Callovian boundary in the exposed sequence. These authors Mandwal and Singh (1993) reported new foraminiferal genus *Indomarssonella* with three species described from the Bathonian sediments of Jhurio hill, Kachchh. They placed the new genus into subfamily Paravalvulininae of the family Chrysalidinidae in view of its close resemblance with *Pseudomarssonela* Redmond in test morphology.

In their subsequent paper, Mandwal and Singh (1994) reported ninety-five species of foraminifera from Patcham and Chari formations of Jhurio hill (Jhura Dome), Kachchh, Western India. They assigned the species to 47 genera belonging to eighteen superfamilies. On the basis of the foraminiferal assemblage these authors also suggested a Bathonian – Oxfordian age for the Patcham and Chari formations of Jhurio hill and demarcated the Bathonian/Callovian as well as Callovian/Oxfordian boundaries in this area.

Pandey and Dave (1993) presented detailed systematics and illustrated account of the Jurassic benthic foraminifera of Kachchh. They selected six surface sections from western Kachchh, *viz.*, Jhurio Dome, Jumara Dome, Habo Dome (Kalajar Nala), Mundhan Anticline, Umia river and Patcham Islands (Khavda Nala) and discussed each section with respect to its geological and stratigraphic setting, abundance and distribution of foraminifera, benthic foraminiferal zonation and chronostratigraphic units. They also made an attempt to define Jurassic- Cretaceous boundary on the basis of foraminiferal assemblages. These authors (*op. cit.*) also suggested Bathonian age to the lower part of Jhurio hill, on the basis of following foraminiferal species: *Epistomina khawdensis, E. regularis, E. coronata, E. ghoshi, Lenticulina bulla, L. dilectaformis, L. tricarinella, L. suturofusus, L. subalata, Vaginulina barnardi, Dorothia poddari, Spirillina polygyrata, Trocholina conosimilis, Garantella* sp., *Saracenaria triquetra* and *Marginulina haynesi*. However, their age assignment is either based on the forms which are long ranging or on the basis of species described from Kachchh basin only.

Dave (1996) introduced Dhosaian stage to the marine sediments comprising Dhosa Shale and Dhosa Oolite of Oxfordian stage. He reported rich benthic foraminiferal assemblages in the type section of Jumara Dome (Jumara formation). The common species include: *Epistomina majungaensis, Lenticulina quenstedti, L. bulla, Haplophragmoides bartensteini* and *Proteonina difflugiformis*. On the basis of foraminiferal assemblages the author identified two foraminiferal *biozones* viz., *Epistomina majungaensis* Range-zone and *E. majungaensis – L. bulla* Interbiohorizon (poorly fossiliferous)-zone and suggested the depositional environment of Dhosaian stage in shallow shelf, open marine environment.

Nandi and Desai (1997) made a detailed diagenetic study of the middle Jurassic carbonates exposed in Jumara, Jhura and Habo hills along the E-W axis of the depositional basin in Mainland of Kachchh. They described the various diagenetic features and interperated the depositional environment of these sediments.

On the basis of their study, they revealed that the depositional and post-depositional changes took place mostly under the pheritic conditions in marine as well as fresh water environments. The evidences gathered by them also suggest diagenesis in a mixed-marine and fresh water as well as burial environment.

Bhalla *et al.* (1998) tried to reconstruct the depositional environment of Jurassic sediments of Chari Formation (Callovian-Oxfordation), exposed at Jhurio hill, Kachchh, on the basis of Carbonate microfacies and foraminiferal palaeoecology. These authors divided the studied sequence into five palaeoecological units, based on foraminiferal assemblages which accumulated in different depositional regimes. The limestones of the Chari sequence were employed to divide the entire sequence into four microfacies which suggested deposition in open beaches, shallow shelves, protected area and deeper part of the shelf. Overall study based on foraminiferal study suggested that the deposition of the Chari sequence exposed at Jhurio hill, Kachchh took place in a near shore, shallow marine basin which was tectonically unstable.

Dubey and Chatterjee (1999) broadly described the paleoclimate and depositional history of Mesozoic Basin of Kachchh, Gujarat and selected five consecutive domes from NW to SE, *viz.*, Ghuneri, Sahera, Mundhan, Jara and Jumara for this purpose. In the studied area, oldest rocks are of Bathonian age, exposed in the centre of Jumara dome whereas the youngest rocks are of Late Cretaceous age are exposed on the southwest periphery (below laterites) in Ghuneri dome. During their study these authors (op. cit.) observed that the

Mesozoic sandstones of Kachchh basin contain detritals derived from coarsely crystalline parent rocks which were transported for relatively short distances before accumulating in coastal environments. The systematic variation in compositional maturity of Mesozoic sandstone suggested the change in paleoclimate of western India (arid/semiarid/semihumid/humid) from middle Jurassic to Late Cretaceous. The samples plotted on QFR ternary diagram exhibit clustering of samples in arid and humid fields. This suggested gradual removal of unstable minerals and rock fragments in humid climates. Petrography of sandstone reveals less dissolution of grains during diagenesis and lithification.

Bhalla *et al.* (2000) synthesized foraminiferal assemblage from Chari Formation (Callovian-Oxfordian), Jhurio hill, Kachchh with petrography and diagenetic study for interpreting the depositional environment, provenance and diagenetic pattern of the studied sequence. The dominance of nodosariids in assemblages indicates a shallow near shore, open marine environment of deposition. These authors observed that the different proportions of calcareous and arenaceous species at different levels in the sequence indicate occasional shifting of shoreline and also suggest the unstable nature of the basin in which Chari sediments were deposited. For the study of the provenance of the sandstone in light of plate tectonics, these authors employed the Qt-F-L and Qm-F-Lt triangular diagrams of Dickinson. These two plots of the samples from the Jhurio area suggested that the sandstones were derived from continental block orogenic provenance. These authors also made an attempt to study the diagenetic pattern of Jhurio hill sandstones that demonstrates a close relation to various phase of subsidence and uplift in the tectonically unstable sandstone from the time of deposition. Uplift of the area caused fresh water dissolution of carbonate and partial oxidation of iron.

Gaur and Singh (2000) described and illustrated a foraminiferal assemblage from Jurassic sequence of Kaiya hill, Kutch comprising forty-four species. Based on the forarniniferal assemblage, these authors (*op. cit.*) assigned a Callovian-Oxfordian age to the studied sequence and divided it in to four biozones.

Gaur and Sisodia (2000) recorded forty-one foraminiferal species from Jurassic rocks of Keera hill, Kachchh. These authors (*op. cit.*) marked four benthic foraminiferal biozones within the studied sequence on the basis of the recovered assemblage.

Talib and Gaur (2005) discussed forarminiferal palaeoecology, microfacies and paleoenvironment of Middle-Upper Jurassic sequence of Jumara hills and divided the studies sequence into five palaeoecological units. They (*op. cit.*) interpreted that the Chari Formation exposed at Jumara hills were deposited in a tectonically unstable shelf zone, as indicated by fluctuations in the shoreline.

Talib and Bhalla (2006a) described the composition and discussed the age of the Chari Formation exposed at Jhurio hill, Kutch. Using few diagnostic foraminiferal species confined to or frequently recorded from Callovian-Oxfordian sequences of different parts of the world, these authors (Talib and Bhalla, 2006a) suggested a Callovian to Oxfordian age to the Chari Formation exposed at Jhurio hill, Kachchh. Callovian Oxfordian boundary was also marked by these authors (*op. cit.*) in the studied sequence. In a subsequent publication, Talib and Bhalla (2006b) discussed affinity and palaeobiogeography of the Middle to Upper Jurassic foraminiferal assemblage from Jhurio Hill, Kutch.

Talib and Faisal (2006) reported fifty- three species of foraminifera from Fakirwari Dome, Kutch includeding twenty-five species which were recorded for the first time from the Indian region. These authors (*op. cit.*) also briefly discussed the age, palaeoecology, and palaeobiogeography of the recovered foraminiferal assemblage. In a later publication, Talib and Faisal (2007) recorded forty spcies of foraminifera from the Jurassic sediments exposed at Ler Dome, Kutch. The foraminiferal assemblage included eighteen species recorded for the first time from the Indian region. These authors (*op. cit.*) also presented a brief account of the age, bathymetry and palaeobiogeography of the foraminiferal assemblage.

Talib *et al.* (2007) delineated the Callovian/ Oxfordjan boundary in two sections exposed in Jumara and Jhurio hills, Kutch on the basisi of some characteristic foraminiferal species.

Talib and Gaur (2008) gave a in detailed account of the affinities and palaeobiogeography of the Middle to Late Jurassic foraminifera recovered from Jhurio hill, Kutch.

Gaur and Talib (2009) described and illustrated a fairly rich foraminiferal assemblage including 51 species, having an overwhelming majority of the families Vaginulinidae and Nodosariidae, from the Chari Formation of Jumara hills, Kutch. These authors (Gaur and Talib, 2009) also suggested a Callovian to Oxfordin age for the studied sequence and also discussed palaeoecology and palaeobiogeography of the foraminiferal assemblage.

Ahmad *et al.* (2000; 2006; 2008) published a detailed account of the petrofacies and diagenetic aspects. The compositional study of sandstones suggested that the major source of the sediments were Purana schist, granites, associated pegmatites and basic rocks. The petrofacies plots of Qt-F-L, Qm-F-Lt and Qp-Lv-Ls suggested that the detritus were derived from continental block and recycled orogen provenance and were deposited in rifted basin setup. These authors also observed that the sandstones were cemented by iron-oxide, carbonate and silica cements and show good amount of existing porosity. This porosity evolution was mainly controlled by early cementation and mechanical compaction.

CHAPTER 3

GEOLOGY OF THE AREA

The Kachchh sedimentary basin embraces entire Kachchh region and the western part of the Banaskantha district of northern Gujarat. The basin is an East-West embayment opening out and deepening to the west towards the Arabian sea and is filled with sediments ranging in age from Middle Jurassic to Holocene. Deccan Trap lava flows of Late Cretaceous to Early Paleocene age divide the Mesozoic and Tertiary rocks of the region. Mesozoic sediments which are more than 2430 m thick, fill the major part of the basin whereas Tertiary sediments with a thickness of 300m, are present in the outer part of the basin bordering the Mesozoic uplifts.

The Kachchh basin is a pericratonic embayment between Nagar Parkar uplift in the north, Kathiwar uplift in the south and Radhanpur – Barmar arch in the east, a sloping platform featured by parallel east-west fault ridges and a median high across them. The northern margin of the basin is faulted along Nagar Parkar fault. The structural axis of the basin plunges southwest, trending parallel and close to the southeastern margin along Kathiwar uplift. The sediments were laid down on a crystalline basement composed of Archaen and Proterozoic rocks (Biswas and Deshpande, 1968).

The Mesozoic rocks of Kachchh range from Middle Jurassic to upper Cretaceous. Of these, Jurassic rocks are exceptionally well developed and exposed in three parallel anticlinal chains of ridges trending in NW-SE direction and an isolated rock mass in the east, near Wagad (Wynne, 1872; Rajanath, 1932; Poddar, 1959). The northern chain is 161 km long and forms a number of islands in Rann of Kachchh namely Patcham, Khadir, Bela and Chorar from west to east. These islands divide the Great Rann of Kachchh from Banni plain. The middle chain is most prominent, extends for 193 km. from Lakhpat in the northwest to Habo in the east, and broken up into a series of domes. The eastern end of this range is separated by a plain from another island lying to the northeast of Kachchh known as Wagad Island. The strike of the Wagad rocks is not in continuity either with northern chain or with middle chain but is intermediate between the two. According to Wynne (1869), the continuation of the

Wagad rock is concealed beneath the silts of the Rann. The southernmost chain forms 64 km long Katrol-Charwar range in the south of Bhuj.

The three articlinal chains are doubly plunging and due to the quaquaversal nature of the dips, they standout as isolated domes with an east-west alignment. The domes are very well developed in northern and central parts of Kachchh and 'Keera hill' is one of the prominent domes in the middle chain. The northern limbs of all the three anticlinal chains are considerably steeper than the southern limbs. There is a prominent syncline between the northern and middle anticlinal chain, lying beneath the silt of the Rann and Banni plain. The Tertiary rocks are mainly restricted to the synclinal area. The outcrops are separated by vast covered plains which comprise the Great and Little Ranns of Kachchh and Banni (grass land) plain. The total area of Kachchh sedimentary basin is about 26400 sq Km., of which outcrop area is only 8000 sq km.

There are four major faults in the Kachchh region trending in an east-west direction. The first fault is situated in the north, immediately north of the first anticlinal chain in the Rann of Kachchh. The second fault runs along eastern Kachchh, passing through the Banni plain. The third fault passes through extreme north of the Kachchh mainland, just touching the northern fringes of Jhurio and Habo hills while the fourth one stretches along the Katrol-Charwar ridge, south of Bhuj.

Jurassic rocks of Kachchh region overlie a Precambrian crystalline basement and have been intruded by basic rocks in form of sills, dykes, laccoliths and volcanic plugs. Laccoliths associated with domes are seen in mainland. The igneous activities are genetically related with the Deccan Trap.

The basin history started with an initial transgression in the early Jurassic followed by regression in early Cretaceous when the basin was completely filled and the Tertiary sedimentation commenced, with the early Eocene transgression after the end of Deccan volcanic activity and eroded with late Miocene-Pliocene regression (Biswas, 1982). The sedimentation was punctuated by repetitive tectonic episodes causing many transgression-regression cycles and breaks in sedimentation.

REGIONAL STRATIGRAPHY

The first stratigraphic sequences of Jurassic of Kachchh was worked out by Wynne (1872) and mapped on the basis of two divisions 'Lower Jurassic group' and 'Upper Jurassic group'. However, the divisions have been referred to as 'Lower series' and 'Upper series' respectively at many places in the text. Waagen (1871, 1873-1876) divided the Jurassic rocks of Kachchh into four divisions and called them 'Group'. These are Patcham, Chari, Katrol and Umia in an ascending order. Gregory (1893, 1900), Kitchin (1900, 1903), Spath (1924, 1927-1933) and Cox (1940, 1952) also worked on Jurassics of Kachchh and followed the stratigraphic division given by Waagen. Later, Oldam (1893), Vredenburg (1910), Wadia (1957), Krishnan (1968), Pascoe (1959) and others, while compiling textbooks freely used time stratigraphic terms such as 'Series', 'Stage' as well rock-stratigraphy term such as 'Bed' to qualify Patcham, Chari, Katrol and Umia. Pascoe (1959) followed chronostratigraphic terminology for designating major subdivision of the Kachchh Jurassics i.e. Patcham series, Chari series, Katrol series and Umia series. Rajnath (1932, 1942) who worked on the mainland of Kachchh introduced a new unit, Bhuj 'Series' overlying Umia, together with the divisions recognized by Waagen. Spath (1933) has designated these subdivisions as 'Group' and Poddar (1964) has preferred to call these as 'Formation'.

Biswas (1971, 1977) proposed a new classification as Jhurio Formation, Jumara Formation, Jhuran Formation, Bhuj Formation in an ascending order.

However, for the purpose of the present study, the classification proposed by Sastry and Mamgain (1971) which is adopted and modified by Kumar (1985), with certain modifications in age as a result of recent researches, has been followed (Table 1). This classification is based on extensive research and is widely accepted.

Patcham Formation

The Patcham Formation is the oldest formation of Kachchh Jurassic sequence and was named after Patcham Island in Rann of Kachchh. The Patcham rocks are dipping southward with a low angle.

Table 1: Mesozoic Succession of Kachchh (after Kumar, 1985)

Formation	Subdivisions	Characteristic fossils
	Deccan Traps	
BHUJ	---------unconformity---------------------	
	Umia Plant Beds (= Zamia Shale)	*Ptilophyllum* flora
	Ukra Beds (calcareous shale)	*Australiceras* sp.
UMIA	sandstones and shale	Unfossiliferous
	Trigonia Beds	*Trigonia*
	Umia Ammonite Beds	*Virgatosphinctes* sp.
	Upper Katrol Shale	*Hildoglochiceras*
	Upper Katrol Sandstone	mainly unfossiliferous
	Middle Katrol Sandstone	*Torquatisphinctes* sp. and
KATROL		*Katroliceras*
	Lower Katrol Beds	ammonites
	Belemnites Marl of Jurun	*Belemnites*
	Kantkote Sandstone	*Euapidoceras*, *Taramelliceras* sp.
	Dhosa Oolite	*Mayaites*, *Epimayaites*
	Athleta Beds	*Metapeltoceras*, *Peltoceras* and
		Reineckeites
CHARI	Anceps Beds	*Kinkeliniceras*, *Hubertoceras* sp.
		Indosphinctes sp
	Rehmanni Beds	*Reineckeia tyranniformis*, *R. rehmanni*
	Macrocephalous Beds	*Macrocephalites*, *Dolikephalites*
	Coral Bed	*Macrocephalites*, *Sivajiceras*,
		Procerates
	Shelly Limestone	*Macrocephalites* sp.
PATCHAM	Kaur Bet Beds	*Corbula lyrata*, *Protocardia*
		pseudotrapezium
---------unconformity--------------------		

Precambrian Basement (not exposed)

The lower part of Patcham Formation is referred to as 'Kuar Bet beds' consisting of sandstones and limestones with some shale bands containing abundant Bathonian pelecypod fauna such as *Corbula lyrata, Protocardia*, etc. These beds are followed by 'Patcham shell' and 'Patcham coral beds' composed of limestones, shales and marls with a rich assemblage of corals, brachiopods, pelecypods and ammonites including the characteristics fossil *Macrocephalites triasngularis* and *Sivajiceras congener* indicating Callovian age for these beds. The total thickness of Patcham Formation is estimated to be 300 m and assigned a Bajocian to Callovian age.

Chari Formation

The Chari Formation conformably succeeds the Patcham Formation and its name was derived from village Chari, 50 km. west-north-west of Bhuj. The Chari Formation consists of thick succession of sandy limestones, marls, calcareous and sandy shales, and oolitic limestone. The formation is best exposed near village Habo which is very close to Chari village in the mainland of Kachchh. This formation yielded a rich and varied megafaunal assemblage of Cephalopods, especially ammonites, with some brachiopods, pelecypods, etc. It has been divided into five sub divisions.

The Chari formation commences with the '*Macrocephalus* beds' containing the characteristic fossil *Macrocephalites macrocephalus.* These beds have been further subdivided by the use of ammonities. The lower *Macrocephalus* beds consist of white limestone intercalated with shale and characterised by the presence of *Macrocephalites triangularis.* The middle and upper parts of *Macrocephalus* bed contain shale and limestone with iron-coated, calcareous, oolitic grains displaying a golden colour, the 'Golden Oolitie', which is locally distributed in the Kachchh region. The fauna of this bed consists of a large number of cephalopods, including the characteristics fossil *Indocephalites diadematus* (Waagen). The common fossils of this bed are *Indocephalites diadematus, Macrocephalites chariensis, Astarte* spp. and some belemnites. *Rahmanni* beds overlie *Macrocephalus* beds and are mostly composed of limestone. This bed is also subdivided into Lower and Upper Rahmanni beds. The lower part consists of yellow limestone having characteristic fossil *Reineckeia rehmanni* while the upper part also contain yellow limestone with characteristic fossils *Reineckeia tyranniformis* and *Idiocycloceras*. Overlying this is '*Anceps* beds' comparising sandy calcareous shale with *Indosphincetes* sp. in the lower part and yellowish limestone with *Kinkeliniceras* and *Hubertoceras* sp. in the upper part. The characteristics fossil of this bed is *Perisphinctes anceps* along with abundant *Terebratula* and cephalopods. These three subdivisions range from lower to middle Callovian in age. The succeeding '*Athleta* beds' are mainly composed of light grey shales with bands of white, yellow or brown limestone. Characteristic fossil of these beds is *Ammonites* (*Peltoceras*) *athleta*. In addition to ammonites numerous species of pelecypods with lamellibranchs and some fish remains are also found. The *Athleta* beds are of upper Callovian age. Dhosa oolite is the topmost bed of Chari Formation, composed of green, redish or brown oolitic limestones, sometimes sandy but often nodular. They contain abundant cephalopod fauna with *Mayaites, Epimayites, Peltoceratoides, Euaspidoceras, Dhosaites, etc.*, pelecypods and terebratulids. This division belongs to Lower Oxfordian age. Total thickness of Chari Formation is about 366 m and it ranges in age from Lower Callovian to Lower Oxfordian.

Katrol Formation

Katrol Formation is named after the east-west trending Katrol Charwar range in the south of Bhuj. This formation overlies the Chari Formation and is chiefly composed of shales, limestone, sandstones and grits with lenticular beds of gypseous sandy shale, although upper part of this formation is dominated by sandstones. Katrol Formation contains abundant cephalopods and pelecypods and has been subdivided into Kantkote sandstones, Belemnite marls of Jurun, Lower Katrol beds, Middle Katrol sandstone, Upper Katrol sandstone and Upper Katrol shales in an ascending order.

The 'Kantkote sandstones' comprise gray or pinkish shales in the lower part while the upper part contains fine to coarse grained, gray and pinkish sandstones. The rich ammonite assemblage having *Dichotomosphinctes, Epimayites, Discosphinctes, Torquatisphinctes, Neaspidoceras, etc.* The assemblage also includes *Trigonia smeei* Sowerby and indicates an Upper Oxfordian age. The succeeding 'Belemnite marls of Jurun' are composed of marls with Belemnites, *e. g., Hibolites* spp., and some cephalopods which suggest an early Kimmeridgian age. The overlying 'Lower Katrol beds' consists of shales with some sandstones and marls with abundant cephalopods, *e.g., Hibolites katrolensis, Phylloceras saxonicum, Taramelliceras kachhense, Glochiceras deplanatum.* This is followed by 'Middle Katrol sandstone' consisting of brown and red sandstone having a prolific *Pachysphinctes* and *Katroliceras* fauna. The faunal assemblage of Lower and Middle Katrol indicates a middle Kimmeridgian age. The 'Upper Katrol sandstone' is unfossiliferous and doubtful record of *Aulacosphinctoides meridionalis* Spath, suggests a Late Kimmeridgian age for the Upper Katrol sandstone. The overlying 'Upper Katrol shale' includes the Narha and Gajansar beds which are regarded as the top of Katrol Formation. They contain several species of *Hildoglochiceras* and *Subdichotomoceras* with *Phylloceras, Ptychophylloceras, etc.,* but *Haploceras elimatum* (Oppel) is most common. These shales are of Portlandian age. Katrol Formation attains a thickness of about 300 m. and ranges in age from Upper Oxfordian to Portlandian.

Umia Formation

This formation conformably overlies the Katrol Formation and is named after Umia village in the western Kachchh. This formation mainly comprises white, pale brown, occasionally variegated sandstones with subordinate ferruginous, hard black or brown grit and few thin bands of shale.

Umia Formation commences with the 'Umia ammonite bed' which consists of sandstones, and shales with conglomerate. The ammonites are abundant fauna being dominated by species of *Virgatosphinctes,* particularly *V. denseplicatus* (Waagen). Marine fossils are rare in the rest of Umia Formation. The overlying '*Trigonia* beds' comprise sandstones having characteristic fossil *Trigonia crassa* Kitchin and *T. ventricosa* Krauss and few other species of *Trigonia.* These beds are followed by 'unfossilifereous shales and sandstones' and, in turn, overlain by 'Ukra beds' consisting of marine calcareous shale with *Australiceras* sp. The total thickness of Umia Formation is about 900 m. On the basis of fossil evidence Umia Formation is assigned a Tithonian to (?) Neocomian age.

Bhuj Formation

Bhuj Formation is the topmost formation of Jurassic succession. It is also known as 'Umia plant beds', consisting of shale with abundant plant fossils. The characteristic fossils of this bed is *Ptilophyllum.* Other plant fossils including *Filicales, Cycadophyta, Conifers* and *Incertae* have also been reported from these beds. Bhuj Formation has a total thickness of about 450 m. and corresponds to Aptian age.

GEOLOGY AND STRATIGRAPHY OF KEERA HILL

Keera hill is named after 'Keera Dunger' a small hill (made up of basic igneous rocks) situated in the northern part of this hill. The hill acquired the shape of an elliptical dome due to quaquaversal nature of dips and is about 9 km in length and 6 km in width, covering an area of about 54 sq Km. The northern flank of the hill is steeply dipping (30^{o}-70^{o}) while southern flank is gently dipping 5^{o}-30^{o}).

Jurassic rocks exposed in the Keera hill belong to Chari and Katrol formations. Both of these are riddled with basic dykes and sills presumably related to Deccan Trap igneous activity. The area is truncated by a major fault running in NNE to SSW direction and it is possible that the fault is related to this igneous activity. There are also several minor radial faults but dislocations of beds are not pronounced. The direct contact between Chari and Katrol Formation is only seen in north, south and southwestern parts of the area (Figure 3).

For the purpose of forminiferal studies, a well-exposed section along a Nala cutting was selected, in the south eastern flank of Keera hill (Figure 3). Chari Formation is excellently developed along this section while Patchum, Umia and Bhuj formations are not exposed in this area. The Katrol Formation is exposed in the north, south and southwestern flanks of the hill and consists mainly of sandstones.

The sandstones samples of Katrol Formation were collected from north, south and southwestern flanks of the hill for petrofocies and digenetic analyses.

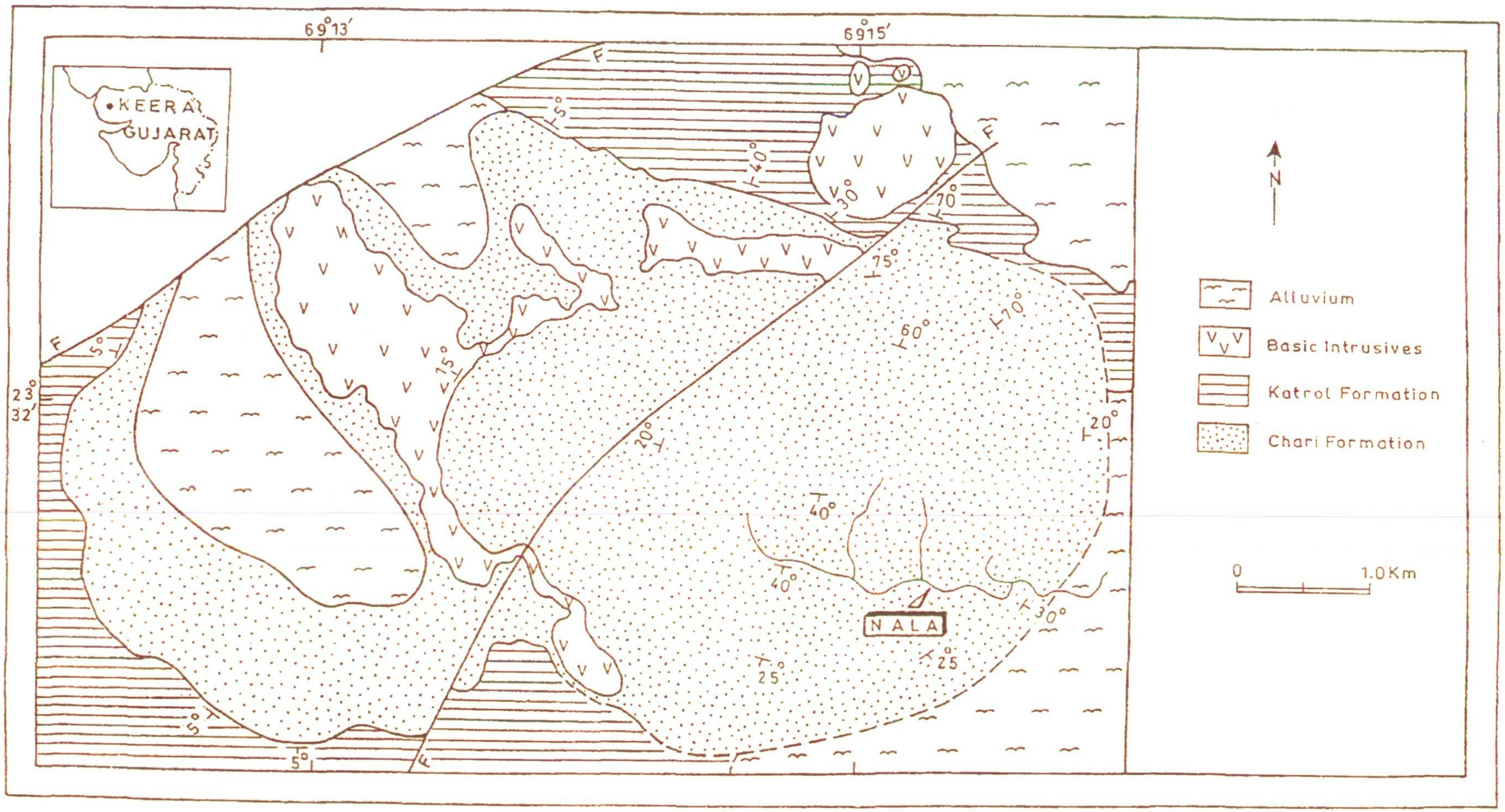


Figure 3: Geological map of Keera hill, Kachchh

Chari Formation

The rocks of Chari Formation are extensively developed at the Keera hill and well exposed along the studied section. They comprise mainly of different varieties of limestones - oolitic, argillaceous, marly, gypsiferous, and sandy whereas the shale beds are intercalated with several thin fossiliferous flagstone bands. A total nine beds have been marked on the basis of lithological variation (Figure 4).

Limestones are yellow, gray, brown with different shades of red and white colour. These are often hard, compact, massive and thickly bedded and occasionally thinly bedded. The limestone bed contains a variety of megafossils such as brachiopods, ammonite, belemnoids, cephalopods and gastropods. During the course of the present study, 15 m thick sequence of yellowish-grey, hard, compact, medium to coarse grained, limestone intercalated with thin fossiliferous flagstone band, has been identified in the central part of the Keera hill which is overlain by yellow to golden colour, hard, compact, massive, coarse grained, oolitic limestone intercalated with shale and marl. The top most bed of the 'Chari Formation' is Dhosa Oolite which is yellowish-brown, hard, compact, fossiliferous, oolitic limestone intercalated with marl. Chari Formation, whose base is not exposed in the Keera area, attains a thickness of about 210 m.

Katrol Formation

Katrol Formation is well developed in the north, south and southwestern parts of Keera hill. It lies conformably above the 'Dhosa Oolite', the topmost bed of Chari Formation. The Katrol Formation is dominated by sandstones which are redish to redish-brown, ferruginous, medium to fine grained, hard and compact, sometime intercalated with soft, friable, white, yellowish, green and gray colour sandstones. These rocks are generally unfossiliferous and strata show low dips (15^o-25^o). The Katrol sandstones of the area are thickly bedded but occasionally show thin laminations. They exhibit sedimentary structures like planner cross bedding, trough cross bedding, ripple marks, parting lineation, etc. These rocks are covered by a thick blanket of alluvium and wind blown sand.

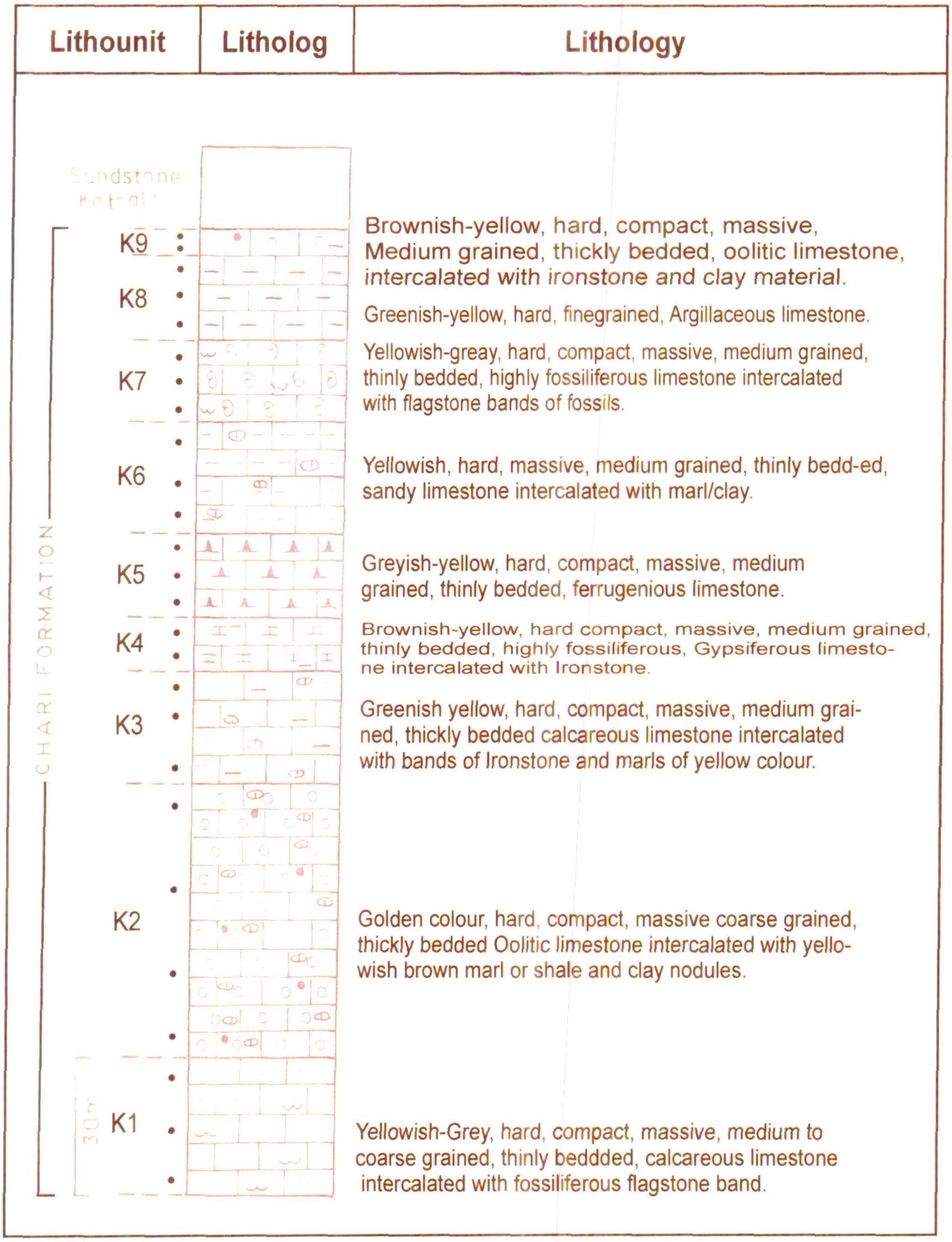


Figure 4: Litholog of Middle-Upper Jurassic sequence exposed at Keera hill, Kachchh

CHAPTER 4

SYSTEMATIC DESCRIPTIONS

The latest classification proposed by Loeblich and Tappan (1988) has been followed in present work. In the past, different workers advocated different classifications and followed from time to time. Only few characters which authors considered important were emphasized while ignoring other, equally significant, features of systematic value. The classification adopted by Loeblich and Tappan (1988) embraces nearly all the prominent diagnostic characters as well as phylogenetic relationship. Their approach is more advanced than any other classification of Foraminiferida proposed to date. It is mainly for this reason that it has been followed.

In the present work, the different genera of foraminifera have been arranged according to the classification proposed by Loeblich and Tappan (1988) whereas various species within single genus arranged alphabetic order. The synonymies have been reduced to a considerable extent and those references concerning important change in generic names or species closely resembling to ours, have only been citied. In order to avoid repetition, suffix *et syn* has been added to the references which contain satisfactory synonymies.

Order	FORAMINIFERIDA Eichwald, 1830
Sub order	TEXTULARIINA Delage and Herouard, 1896
Super family	HORMOSINACEA Haeckel, 1894
Family	HORMOSINIDAE Haeckel, 1894
Sub family	REOPHACINAE Cushman, 1910
Genus	REOPHAX de Montfort, 1808

***Reophax* aff. *R. suevica* Franke**

Plate I, Figure 1

Reophax suevica FRANKE, 1936, p. 19, p. 1, fig. 19.

Reophax suevica (Franke) – NAGY and JOHANSON, 1991, p.20, pl.2, figs.6-9.

Description: Test large, elongated, compressed, slightly curved; chambers well marked, three in number, uniserial, rectilinear, slightly longer than broad enlarging gradually as added; sutures distinct, simple, depressed, straight to somewhat oblique; apearture indistinct, appears to be terminal, rounded; wall arnaceous, fine to medium grained; surface moderately rough.

Dimensions (in mm): Length 0.40 to 0.42, width 0.14 to 0.16.

Remarks: A specimen of *Reophax* showing affinity with *R. suevica* Franke, 1936, was recorded from the present material. Nagy and Johanson (1991) also described and illustrated this species from Jurassic (Toarciam- Bajocian) deposits of the

Statfjord and Gulfaks fields in the northern North Sea which show close resemblance with our specimen. However, our form possesses lesser number of chambers.

Occurrence: Rare

Repository of type material: *AMUGD* Cat. No. MF. *504*

Super family LITUOLACEA de Blainville, 1827

Family LITUOLIDAE de Blainville, 1827

Sub family AMMOMARGINULININAE Podobina, 1978

Genus AMMOBACULITES Cushman, 1910

***Ammobaculites coprolithiformis* (Schwager)**

Plate I, Figure 2

Haplophragmium coprolithiformis SCHWAGER, 1867, p.654, pl.34, fig.3
Ammobaculites coprolithiformis (Schwager) – GORDON, 1967, p.449, pl.1, fig. 4, *et syn.* - BHALLA and TALIB, 1991, pp. 94-95, pl. I, fig. 16; fig. 5, *et syn.*

Description: Test medium, elongated; early portion planispiral, coiled, involute, with three triangular chambers, increasing irregularly in size as added; suture indistinct, simple, depressed, radial, straight to somewhat curved in early portion; later portion uniserial, rectilinear, with two well-marked broad chambers, enlarging irregularly as added, last chamber somewhat inflated, conical, longer than broad; sutures of uniserial portion indistinct, simple depressed, straight to slightly curved; periphery lobulate; apearture indistinct, appear to be terminal, rounded; wall coarsely arenaceous, surface rough.

Dimensions (in mm): Length of test 0.24, length of uncoiled portion 0.16, width of uncoiled portion 0.12, diameter of coiled portion 0.14, diameter of last chamber 0.10.

Remarks: *Ammobaculites coprolithiformis* was originally described by Schwager (1867) from the Bajocian of Wuerttenberg. It has been reported from Lias as well as Middle and Upper Jurassic (Callovian-Kimmeridigian) of various parts of the world and is found to occur abundantly in Oxfordian. Two specimens of *A. coprolithiformis* (Schwager) were found in present material, which closely resemble the forms recorded by Gorden (1962, 1965, 1967) from the Upper Jurassic of England and Scotland. Bhalla and Talib (1991) also recorded this species from Jurassic sediments of Jhurio hill, Kachchh and made a detailed study on its variation. Our forms come well within the range of variation as worked out by Bhalla and Talib (*op. cit*).

Occurrence: Rare

Repository of type material: AMUGD Cat No. MF. 505

***Ammobaculites nanogyrus* Nagy and Seidenkrantz**

Plate I, Figure 3

Ammobaculites nanogyrus NAGY and SEIDENKRANTZ, 2003, p. 35-36, pl. 3, figs. 1-16. *et syn.*

Description: Test medium, elongated; early portion planispiral, slightly compressed, involute, with three triangular chambers, increasing irregularly in size; sutures of early portion simple, depressed, radial, nearly straight; later portion uniserial, rectilinear, chambers well-marked, two in number, somewhat inflated, enlarging gradually as added; suture of uniserial portion distinct, simple, depressed, straight to slightly curved, perpendicular to test axis; periphery lobulate; apearture indistinct, appear to be terminal, rounded; wall coarsely agglutinated; surface rough.

Diamensions (in mm): Length of test 0.29, diameter of coiled portion 0.10, width of uncoiled portion 0.13, length of uncoiled portion 0.20.

Remarks: *Ammobaculites nanogyrus* was originally described by Nagy and Seidenkrantz (2003) from Jurassic deposits of Denmark. Our forms are very close to specimens from Denmark in shape, size, number of chambers in the coiled and uncoiled portion as well as nature of suture and come well within the range of variation of this species.

Occurrence: Rare

Repository of type material: AMUGD Cat. No. MF. 506

Sub order INVOLUTININA Hohenegger and Piller, 1977

Family INVOLUTINIDAE Butschli, 1880

Sub family INVOLUTININAE Butschli, 1880

Genus TROCHOLINA Paalzow, 1922.

***Trocholina conosimilis* Subbatina and Srivastava**

Plate I, Figure 4

Trochalina conosimilis SUBBOTINA and SRIVASTAVA *in* Subbotina *et al*; 1960; pp. 41-42, pl. 4, fig. 5a-c.

Trocholina conosimilis (Subbotina and Srivastava) – BHALLA and TALIB, 1991, p.104, pl. IV, figs.11,12 *et syn.*-PANDEY and DAVE, 1993, p.125, pl.2, figs. 7-8.

Description: Test medium, sub conical, with broad apical angle, steep peripheral margin, trochospiral, low-spired, spiral side evolute; spherical proloculus followed by spiral, undivided, tubular, second chamber, making four to five closely coiled whorls; suture spiral, distinct, slightly limbate, depressed in early portion, slightly raised to flush in later part; ventral side poorly preserved, involute, flat; umbilical area spherical, filled with calcareous material; aperture indistinct, appears to be at open end of tube; wall calcareous, surface smooth.

Dimension (in mm): Diameter 0.12 to 0.24, height 0.05 to 0.15.

Remarks: The present form of *Trocholina conosimilis* are similar to those described originally by Subbotina and Srivastava (1960) from the Jurassic (Oxfordian) sediments of Kachchh. Bhalla and Talib (1991) also described these species from the same region. Subbotina and Srivastava (*op. cit.*) observed it having sharp periphery. However, in the present material, specimens with sharp to blunt peripheral margin and limbate sutures are found which are similar to those described by Bhalla and Talib (1991).

Sub order SPIRILLININA Hohenegger and Piller, 1975

Family SPIRILLINIDAE Reuss and Fritsch, 1861

Genus SPIRILLINA Ehrenberg, 1843

***Spirillina polygyrata* Guembel**

Plate I, Figure 5

Spirillina palygyrata GUEMBEL, 1862, p. 214, pl. 4, fig 11a-c.

Spirillina palygyrata (Guembel) – BHALLA and ABBAS, 1978, pp. 188-190, pl. 13, figs. 3-4, *et syn.* –BHALLA and TALIB, 1991, P. 103, pl. IV, fig. 10, *et syn.*

Description: Test small, flattened, disc-shaped, slightly compressed; globular proloculus followed by closely coiled, somewhat inflated, tabular, undivided, second chamber, consisting of four to seven whorls; suture distinct, spiral, depressed; aperture simple, at open end of tube; wall calcareous, surface smooth.

Diamensions (in mm): Diameter 0.08 to 0.14, thickness 0.02 to 0.04.

Remarks: *Spirillina polygyrata* was originally described by Guembel (1862) from the Jurassic (Oxfordian) of Germany. The present specimens are similar to those described by Bartenstein and Brand (1937) from the Jurassic (Lias-Malm) of Germany, by Kalantari (1969) from the Jurassic of Iran, and by Bhalla and Abbas (1978) as well as Bhalla and Talib (1991) from the Jurassic rocks of Kachchh. Detailed variation and dimorphism in this species has been worked out by Bhalla and Abbas (1978). *Spirillina polygyrata* shows considerable variation in size and thickness of the test. The number of whorls and the degree of central depression of test also varies. The present specimens come well within the variation range described by Bhalla and Abbas (1978).

Occurrence: Rare

Repository of type material: AMUGD Cat. No. MF. 508

Sub order	LAGENINA Delage and Herouard, 1896
Super family	NODOSARIACEA Ehrenberg, 1838
Family	NODOSARIIDAE Ehrenberg, 1838
Sub family	NODOSARIINAE Ehrenberg, 1838
Genus	NODOSARIA Lamarck, 1812

Nodosaria simplex **(Terquem)**

Plate I, Figure 6

Dentalina simplex TERQUEM, 1858, p. 599, pl. 2, fig. 5a,b.

Nodosaria simplex (Terquem) – KALANTARI, 1969, pp. 73-74, pl. 4, figs. 6, 15-17, *et syn.* – BHALLA and TALIB, 1991, pp. 97, pl. I, fig. 4, *et syn.*

Description: Test medium, broken, only last two chambers present, cylindrical, uniserial, rectilinear; chambers somewhat spherical, two in number, slightly inflated, increasing gradually as added; sutures distinct, simple, transverse, depressed; periphery lobulate; aperture terminal, radiate, situated on a short neck; wall calcareous; surface smooth.

Dimension (in mm): Length 0.20, width 0.12.

Remarks: A broken specimen of *Nodosaria simplex* (Terquem) is recovered from the Kachchh material. It has been recorded by different workers from the Jurassic rocks, including Said and Barakat (1958) from Egypt and Kalantari (1969) from Iran. A comparison of Indian specimens with those from Iran reveals that our specimen comes well within the range of variation. Our specimen closely resembles the form described by Bhalla and Talib (1991) from Jhurio hill, Kachchh and Kalantari (1969) from Jurassic of Iran.

Genus PYRAMIDULINA Fornasini, 1894

***Pyramidulina hortensis* (Terquem)**

Plate I, Figure 7

Nodosaria hortensis TERQUEM, 1866, p. 476, pl. 19, fig. 13.

Pyramidulina hotensis (Terquem) – NAGY, FINSTAD, DYPVIK and BREMER, 2001, p. 349, pl. 2 fig. 3.– NAGY and JOHANSON, 1991, p.25, pl. 5, fig.5, *et syn.*

Nodosaria hortensis (Terquem) – KALANTARI, 1969, pp. 72-73, pl. 4, figs. 21-22, *et syn.*

Description: Test small, elongated, uniserial, rectilinear; chamber spherical, two in number, almost uniform, increasing very slowly in size as added; sutures distinct, simple, transverse, depressed, fairly constricted, perpendicular to axis; periphery labulate; aperture terminal, radiate, situated on a small neck; wall calcareous; surface ornamented with twelve longitudinal costae, uninterrupted by sutures.

Dimensions (in mm): Length 0.10, width 0.05

Remarks: Two well-preserved forms belonging to *Pyramidulina hortensis* (Terquem), 1866 were found in present material. This is a well- known species of *Pyramidulina* and has been described as *Nodoraria hortensis* from Jurassic by several workers including Barnard (1950a, 1950b) and Kalantari (1969). Our specimen closely resemble to forms described by Kalantari (1969) from the Jurassic (Bajocian) sediments of Iran and to those figured by Nagy et al. (2001). *Pyramidulina hortensis* has also been described by Nagy and Johanson (1991) from (Toarcian-Bajocian) of Statfjord and Gullfaks fields in the north North Sea and from Callovian of Scotland (Nagy et al., 2001).

Occurrence: Rare

Repository of type material: AMUGD Cat. No. 510

Subfamily FRONDICULARIINAE Reuss, 1860

Genus FRONDICULARIA Defrance, 1862

***Frondicularia* cf. *F. involuta* Terquem**

Plate I, Figure 8

Frondicularia involuta Terquem, 1866, p.403, pl.15, fig.3a-b.

Frondicularia involuta (Terquem) – KALANTARI, 1969, p.93, pl.3, figs.24-27.

Description: Test large, palmate, flattened; chamber well-marked, seven in number following globular proloculus, chevron shaped, low, increasing in width but very little in height as added; sutures distinct, limbate, elevated, acutely arched upward; periphery entire; apearture distinct, terminal, radiate; wall calcareous; surface smooth.

Dimensions (in mm): Length 0.34, width 0.24, thickness 0.06.

Remarks: A specimen of *Frondicularia* which can be compared with *F. invaluta* (Terquem), 1866, originally described from the Lias of France was found in the present material. Our specimen is somewhat close in appearance to those described by Kalantri (1969) from the Bajocian and Oxfordian of Iran. However, the specimen recovered from our material differs in having limbate and elevated suture as compared to flush sutures of the Iranian form.

Occurrence: Rare

Repository of type material: AMUGD Cat. No. 511

Family VAGINULINIDAE Reuss, 1860

Subfamily LENTICULININAE Chapman, Parr and Collins, 1934

Genus LENTICULINA Lamarck, 1804.

Lenticulina dilectaformis **Subbatina and Srivastava**

Plate I, Figure 9

Lenticulina dilectaformis SUBBOTINA and SRIVASTAVA, 1960, p. 15, pl. 1, fig. 2 a,b.

Lenticulina dilectaformis (Subbutina and Srivastava) - PANDEY and DAVE, 1993, p.128, p. 4 figs.6-9; p. 5, figs.1-4, 5, *et sym.*

Description: Test medium, lenticular, planispiral, involute, tending to uncoil, biumbonate; chambers eight in outer coil, well marked, enlarging gradually as added; sutures distinct, relatively thin, raised, slightly curved, sutures forming raised margin near umbilical area; periphery acute, keeled; aperture simple, radiate at peripheral angle; wall calcareous; surface smooth.

Dimensions (in mm): Major diameter 0.09 to 0.36, minor diameter 0.08 to 0.24, thickness 0.05 to 0.12.

Remarks: *Lenticulina dilectaformis* was first described by Subbotina and Srivastava (1960) from upper Jurassic deposits of Rajasthan (Jaisalmer) and Kachchh. It shows close resemblance with *L. quenstedti* (Guemble) but differs in having tendency to uncoil in later portion and sutures forming raised marginal arch near umbilicus area. *L. quenstedti* is characterised by limbate sutures forming a ring around umbilical area. Our specimens are similar to those described and illustrated by Pandey and Dave (1993) from Jurassic of Kachchh.

Occurrence: Frequent to rare

Repository of type material: AMUGD Cat. No. 512

***Lenticulina discipiens* (Wisniowski)**

Plate I, Figure 10

Lenticulina discipiens WISNIOWSKI, 1890, p.222, pl.10, figs. 5a-b, 11a-b

Lenticulina discipiens (Wisniowski) – PANDEY and DAVE, 1993 pp.128- 129, pl.5, fig. 6-7

Description: Test large, lenticular, planispiral, involute, closely coiled; chambers distinct, ten in last whorl, enlarging gradually as added; sutures distinct, limbate, raised, curved, converging in central part of the test to form a fused mass in umbilical area; periphery entire, prominent, strongly keeled; aperture distinct, simple, radiate at dorsal angle; wall calcareous; surface smooth.

Dimensions (in mm): Major diameter 0.20 to 0.31, minor diameter 0.16 to 0.24, thickness 0.08 to 0.12.

Remarks: A specimen belonging to *Lenticulina discipiens* (Wisniowki) was recovered in our material. A comparison of the present form with those described by Pandey and Dave (1993) from Jurassic of Kachchh, reveals that both are similar.

Occurrence: Rare

Repository of type material: AMUGD Cat. No. 513

***Lenticulina ectypa* (Loeblich and Tappan)**

Plate I, Figure 11

Astacolus ectypus LOEBLICH and TAPPAN, 1950, p.179, pl.1, fig.10.

Lenticulina ectypa (Loeblich and Tappan) – SHIPP and MURRAY, 1981, p.138, pl.6.3.3, figs.7-10.

Description: Test medium, lenticular, planispiral, involute, subrounded, biumbonate; chambers distinct, outer coil with eight chambers, enlarging gradually as added; sutures distinct, simple, strongly depressed, slightly curved, often ribbed on proximal side; periphery slightly lobulate; umbilical area depressed, forming a small circular umbilical ridge; apearture radiate, placed on a small neck; wall calcareous; surface smooth.

Dimensions (in mm): Major diameter 0.10 to 0.32, minor diameter 0.08 to 0.26, thickness 0.05 to 0.12.

Remarks: The present material yielded well-preserved specimens of *Lenticulina ectypa* (Loeblich and Tappan), which show close resemblance to those described and figured by Shipp and Murray (1981) in gross morphological features. Barnard *et al.* (1981) recorded *L. ectypa* from oxford clay (Callovian-Oxfordian of England) having elongated test, uncoiling in later portion and poorly developed sutural ribs. It can also be distinguished by *L. quenstedti* (Guembel) in having depressed sutures and sutural ribs forming a small circular umbilical ridge.

Occurrence: Abundant to rare

Repository of type material: AMUGD Cat. No. 514

Lenticulina muensteri **(Roemer)**

Plate I, Figure 12

Robulina muensteri ROEMER, 1839, p.48, pl.20, fig. 29a-b

Lenticulina muensteri (Roemer) – SHIPP and MURRAY, 1981, p.139, pl.6.3.3, fig.14, 15. – NAGY and JOHANSON, 1991, p. 26, pl. 5, fig. 24-25, pl. 7, fig.8-10.

Description: Test medium, planispiral, involute, subrounded, closely coiled, biumbonate; chambers well-marked, eight to eleven in number, enlarging gradually as added; sutures distinct, limbate, slightly raised to flush, curved; periphery entire, keeled; umbilical area slightly raised with clear boss; aperture distinct, radiate, at dorsal angle; wall calcareous; surface smooth.

Dimensions (in mm): Major diameter 0.09 to 0.31, minor diameter 0.07 to 0.24, thickness 0.04 to 0.14.

Remarks: *Lenticulina muensteri* (Roemer) originally described from the Lower Cretaceous of Germany and also known from the Jurassic, was found in present material. This is a well-known species of *Lenticulina* and has been described by several workers from different Jurassic localities of the world. It shows slight variation in the morphology of the test. Our specimens are similar to those recorded by Shipp and Murray (1981) and Nagy and Johanson (1991). The specimens described by Barnard and Shipp (1981) from Kimmeridgian of Boulonnais slightly differ in having depressed sutures in the uncoiled part whereas they are flush or slightly raised on the coil. *L. munsteri* (Roemer) was commonly found with *L. Subalata* (Reuss) in the present material. From Kachchh, this species has been described by Subbotina *et al.* (1960) having somewhat depressed sutures and elevated central disc. Subsequently, Bhalla and Abbas (1978) observed it from same region having non-elevated central disc.

Occurrence: Abundant to rare

Repository of type material: AMUGD Cat. No. 515

Lenticulina quenstedti **(Guembel)**

Plate I, Figure 13

Cristellaria quenstedti GUEMBEL, 1862, p. 226, pl. 4, fig. 2a, b

Lenticulina quenstedti (Guembel) – BHALLA and ABBAS, 1978 p. 180, pl. 6, fig.4, *et syn.* – BHALLA and TALIB, 1991, p. 99, pl. II, fig. 7, *et syn.*

Description: Test medium to large, lenticular, planispiral, involute, tightly coiled, biumbonate; outer coil with eight to nine chambers, well marked, enlarging gradually as added; sutures distinct, limbate, raised, curved, coalesce near umbilicus to form a ring around it; periphery acute, keeled; apearture simple, radiate, at peripheral angle, placed on a short neck; wall calcareous; surface smooth.

Dimensions: (in mm): Major diameter 0.12 to 0.32, minor diameter 0.10 to 0.26, thickness 0.06 to 0.14.

Remarks: The Indian specimen described here are similar to those recorded by Kalantari (1969) from Jurassic of Iran, showing markedly raised sutures and well-developed keel. Our forms are robust and well preserved having clear umbilical ring as compared to those described by Bhalla and Abbas (1978) and Bhalla and Talib (1991) from Jurassic sediments of Kachchh.

A detailed study of variation in *L. quenstedli* was carried out by Bhalla and Talib (1985a) of our specimens come well within the variation ranged worked out by these authors.

Occurrence: Abundant to rare

Repository of type material: AMUGD Cat. No. 516

***Lenticulina subalata* (Reuss)**

Plate I, Figure 14

Cristellaria subalata (REUSS, 1854, p. 68, pl. 25, fig. 13.

Lenticulina subalata(Reuss) – BHALLA and ABBAS, 1978, p. 180-181, pl. 6, fig. 6; pl. 10, figs. 1-4, *et syn.* – BHALLA and TALIB, 1991, p. 99-100, pl. II, fig. 8, *et syn.*

Description: Test medium to large, lenticular, planispiral, involute, rounded to elongated, biumbonate; chambers well marked, seven to twelve in number, triangular in shape, enlarging gradually as added; sutures distinct, limbate, raised, gently curved; umbilical area large, raised, somewhat rounded; periphery entire, prominently keeled; aperture distinct, radiate, at dorsal angle; wall calcareous; surface smooth.

Dimensions (in mm): Major diameter 0.08 to 0.38, minor diameter 0.06 to 0.31, thickness 0.04 to 0.20.

Remarks: This well-known species of *Lenticulina* was originally described by Reuss (1854) from the Cretaceous rocks of Germany. *Lenticulina subalata* (Reuss) shows a wide range of variation in shape and size of the test. A detailed variation study of this species was carried out by Bhalla and Abbass (1975b). These authors observed that some of the species of *Lenticulina* erected by previous workers are in fact different morphovariants of *L. subalata*. These morphovariants were shown to intergrade with one another. The present forms of *L. subalata* are identical to those described by Bhalla and Abbas (1978) and Bhalla and Talib (1991) from Jurassic sediments of Kachchh and exhibit a similar trend of variation. Our specimens are also similar to those described by Cifelli (1959) and Kalantari (1969) from the Jurassic rocks of England and Iran respectively.

Occurrence: Abundant to rare

Repository of type material: AMUGD Cat. No. MF. 17

***Lenticulina* aff. *L. subalata* (Reuss)**

Plate I, Figure 15

Cristellaria subalata REUSS, 1854, p.68, pl. 25, fig. 13.

Lenticulina subalata (Reuss) – BHALLA and ABBAS, 1978, p. 180-181, pl. 6, fig. 6; pl. 10, figs. 1-4, *et syn.* – BHALLA and TALIB, 1991, p. 99-100, pl. II, fig. 8, *et syn.*

Description: Test medium, lenticular, planispiral, involute, rounded to elongated, biumbonate; chamber well marked, nine in number, triangular in shape, enlarging gradually as added; sutures at proximal end distinct, limbate, raised, at distal end, slightly raised, or flush, gently curved; umbilical area small, raised, conical in shape; apearture distinct, radiate, at dorsal angle; wall calcareous; surface smooth.

Dimensions (in mm): Major diameter 0.10 to 0.25, minor diameter 0.09 to 0.20, thickness 0.05 to 0.13.

Remarks: A specimen of *Lenticulina* recovered from present material has affinity with *L. subalata* (Reuss). *Lenticulina subalata* was originally described by Reuss (1854) from the Cretaceous of Germany. However, our specimen differs in having a small conical umbilical area and suture at distal end being slightly raised or flush.

Occurrence: Abundant to rare

Repository of type material: AMUGD Cat. No. 518

***Lenticulina tricarinella* (Reuss)**

Plate I, Figure 16

Cristellaria (Cristellaria) tricarinella REUSS, 1863, p. 68, pl. 7, fig. 9; pl. 12, figs. 2-4.

Lenticulina tricarinella (Reuss) – BHALLA and ABBAS, 1978, pp. 181-182, pl. 6, fig. 9; pl. 11, figs. 1-6, *et syn.* – BHALLA and TALIB, 1991, p. 100, pl. II, fig. 12, *et syn.*

Description: Test medium to large, sub-rounded to elliptical, parallel-sided in front view, very slightly biumbonate; early portion planispirally coiled , with three to five chambers; later portion uncoiled with two to four chambers, forming a rectilinear series, chambers broad, low, enlarging rapidly as added, tending to reach proloculus, outer margin of final chamber occupying half to three-fourth of peripheral margin; sutures distinct, limbate, raised, curved, oblique to axis of coiling; periphery entire, tricarinate; aperture distinct, radiate; wall calcareous; surface smooth.

Dimensions (in mm): Length 0.15 to 0.35, width 0.10 to 0.26, thickness 0.04 to 0.09.

Remarks: *Linticulina tricarinella* (Reuss) is a famous and well-established Jurassic species of *Lenticulina,* first described by Reuss (1863) from Lower Cretaceous of North Germany. It has been reported from various parts of the globe by different workers. A characteristic species in the Middle Jurassic of Europe, it was recorded by Bartenstein and Brand (1937) from the upper Bajocian of northwest Germany. Said and Barakat (1958), Kalantari (1969) and Barnard *et al.* (1981) described and illustrated this species from Jurassic rocks of Egypt, Iran and England respectively.

Our forms are similar to those described by Bartenstein and Brand (1937), Said and Barakat (1958), Kalantari (1969). Barnard *et al.* (1981), Bhalla and Abbas (1978), and Bhalla and Talib (1991). *Lenticulina tricarinella* (Reuss) displays a wide variation in the shape and size of the test as well as the number of chambers comprising coiled and uncoiled portions. A detailed variation of this species has been worked out by Bhall and Abbas (1978)

Occurrence: Frequent to rare

Repository of type material: AMUGD Cal. No. 519

***Lenticulina varians* (Bornemann)**

Plate II, Figure 17

Cristellaria varians BORNEMANN, 1854, p. 41, figs. 32-34

Lenticulina varians (Bornemann) – BHALLA and ABBAS, 1978, p. 182, p. 6, fig. 5, *et syn.* – BHALLA and TALIB, 1991, p. 100, pl. III, fig. 8, *et syn.*

Description: Test small to medium, planispiral, involute, subrounded, tightly coiled; chambers distinct, well marked, eight to nine in outer coil, triangular in shape, enlarging gradually as added; sutures distinct, simple, slightly thickened, depressed, gently curved; periphery lobulate; umbilical area depressed, filled with matrix; apearture distinct, simple, radiate, at dorsal angle; wall calcareous; surface smooth.

Dimensions (in mm): Major diameter 0.08 to 0.31, minor diameter 0.05 to 0.24, thickness 0.03 to 0.13.

Remarks: A few well-preserved specimens of *L. varians* were recovered from the present material. Our forms closely resemble those described by Bhalla and Abbas (1978) as well as Bhalla and Talib (1991) from Jurassic sediments of Habo and Jhurio hills, Kachchh respectively. A comparison of the present forms with those described by Kalantari (1969) from the Iranian Jurassic reveals that the Indian forms have depressed suture and lobulate periphery.

Occurrence: Abundant to rare

Repository of type material: AMUGD Cat. No. 520

***Lenticulina* sp. Indet.**

Plate II, Figure 18

Description: Test small, somewhat oblong, biconvex; chambers well-marked, six in number, somewhat inflated, enlarging rapidly as added; sutures distinct, simple, slightly depressed, curved, ribbed on proximal side; periphery faintly keeled, lobulate in last two chambers; aperture, radiate, placed on a neck, at dorsal angle; wall calcareous; surface smooth.

Dimensions (in mm): Major diameter 0.15, minor diameter 0.11, thickness 0.08.

Remarks: The present material yielded a specimen of *Lenticulina* having some resemblance with *Lenticulina sp.* A of Bhalla and Abbas (1978) described from the Jurassic (Oxfordian-Callovian) sediments of Kachchh. It may represent a new species but more specimens with good preservation are required before a specific name could be assigned.

Occurrence: Rare

Repository of material: AMUGD Cat. No. 521

Genus SARACENARIA Defrance, 1824.

***Saracenaria* aff. *S. triquetra* (Gumbel)**

Plate II, Figure 19

Cristellaria triquetra GUMBEL, 1862, p. 225, pl. 3, figs. 28 a, b.

Saracenaria triquetra (Gumbel) – BHALLA and ABBAS, 1978, p. 184, pl. 7, fig. 10; pl. 12, figs. 1-4, *et syn.*

Description: Test medium, elongated, inflated, triangular in cross-section; outer margin and two angles of apertural face acute; early portion coiled, somewhat compressed, having three to four chambers; later portion uncoiled, inflated, with three to four chambers forming rectilinear series, enlarging gradually as added; suture distinct, simple, slightly raised, gently curved; periphery entire, keeled; apeartural face broad, slightly convex centrally towards apertural end; apearture terminal, radiate, at dorsal angle; wall calcareous; surface smooth.

Dimensions (in mm): Length 0.22 to 0.25, width 0.11 to 0.12, thickness 0.09 to 0.10.

Remarks: Two specimens of *Saracenaria* were found in present material which show affinity with *Saracenaria triquetra* (Gumbel). Bhalla and Abbas (1978) also recorded *S. triquetra* from Jurassic rocks of Habo hill, Kachchh. Our specimens come within the range of variation as worked out by Bhalla and Abbas (1978) but differs in only having slightly raised sutures.

Occurrence: Rare

Repository of material: AMUGD Cat. No. 522

Subfamily MARGINULININAE Wedekind, 1937

Genus ASTACOLUS de Montfort, 1808.

***Astacolus* aff. *A. anceps* (Terquem)**

Plate II, Figure 20

Cristellaria anceps TERQUEM, 1870, p. 428. pl. 9, figs. 11-21

Astacolus anceps (Terquem) – PANDEY and DAVE, 1993, pp. 133-134, pl. 8, fig. 6.

Description: Test medium, oval, compressed, slightly curved; chambers well-marked, low and broad, eight in number with globular proloculus, triangular in shapes, enlarging gradually as added; sutures distinct, slightly limbate, elevated, curved; periphery entire, outer margin faintly keeled; aperture terminal, radiate, at dorsal angle; wall calcareous, surface smooth.

Dimensions (in mm): Length 0.18 to 0.26, width 0.12 to 0.18, thickness 0.08 to 0.09.

Remarks: The specimens which were recovered from the present material are somewhat similar to those described by Pandey and Dave (1993) from the Jurassic sediments of Kachchh.. The specimen of *Astacolus anceps* described by Pandey and Dave (*op. cit*) have more elongated and compressed test.

Occurrence: Rare

Repository of type material: AMUGD, Cat. No. 523

Genus HEMIROBULINA Stache, 1864

***Hemirobulina woodi* (Bhalla and Abbas)**

Plate II, Figure 21

Marginulina woodi BHALLA and ABBAS, 1978, pp.183-184, pl. 7, figs. 8-9.

Marginulina woodi (BHALLA and ABBAS) – Bhalla and Talib, 1991, p. 101, pl. III, figs. 18-19.

Description: Test of medium size, elongated, width slightly increasing with height, nearly parallel-sided, gently arcuate, moderately inflated; early portion loosely coiled, planispiral, later portion uncoiled, rectilinear; chamber well-marked, enlarging gradually as added, coiled portion having four chambers including globular proloculus; uncoiled portion with five broad and low chambers, in uniserial, rectilinear series; sutures distinct, thickened, slightly depressed, gently curved in early portion, nearly straight later on, oblique to axis; periphery entire, slightly keeled; aperture terminal, radiate, at dorsal angle; wall calcareous; surface smooth.

Dimensions (in mm): Length 0.14 to 0.35, width 0.06 to 0.18, thickness 0.04 to 0.11.

Remarks: *Hemirobulina woodi* was originally described by Bhalla and Abbas (1978) from Jurassic (Callovian-Oxfordian) of Kachchh. The specimens recovered from the present material exhibit almost the same range of variation and dimorphism as worked out by Bhalla and Abbas (1978). Our specimens are also similar to those described by Bhalla and Talib (1991) from Jhurio hill, Kachchh. The specimens described by Pandey and Dave (1993) have less prominent keel and size of chambers in slightly larger than the type figure of Bhalla and Abbas (1978).

Occurrence: Abundant to rare

Repository of type material: AMUGD Cat. No. 524

Genus MARGINULINA d'Orbigny, 1826.

***Marginulina haynesi* Bhalla and Abbas**

Plate II, Figure 22

Marginulina haynesi BHALLA and ABBAS, 1978, pp. 182-183 pl.7, fig. 5-6.

Marginulina haynesi (Bhalla and Abbas) – PANDEY and DAVE, 1993, p.134, pl. 9, figs. 10, 11.

Description: Test small, elongated, moderately inflated; early portion arcuate, very slightly planispiral; later portion uncoiled, uniserial; coiled portion having three chambers, enlarging gradually as added; uncoiled portion with four low and broad chambers, increasing gradually at beginning, rather rapidly later on, touching peripheral margin; sutures distinct, simple, curved, almost flush, slightly depressed in later portion; apertural margin entire, peripheral margin slightly lobulate; aperture radiate, slightly protruding, at dorsal angle; wall calcareous; surface ornamented with numerous, prominent, closely spaced, low longitudinal ribs, traversing entire length of test, parallel to apertural margin, gently constricted at sutures.

Dimensions (in mm): Length 0.14 to 0.18, width 0.07 to 0.08, thickness 0.04 to 0.06.

Remarks: This species was originally described by Bhalla and Abbas (1978) from Jurassic of Kachchh. Our specimens resemble very closely with form described by Bhalla and Abbas (1978) and Pandey and Dave (1993). A considerable range of variation in shape, size, and number of chambers in coiled and uncoiled portion was also observed in this species by Bhalla and Abbas (1978).

Occurrence: Rare

Repository of type material: AMUGD Cat. No. 525

Genus VAGINULINOPSIS Silvestri, 1904

***Vaiginulinopsis* sp. indet.**

Plate II, Figure 23

Description: Test large, elongated, somewhat arcuate, compressed, flattened, maximum width at almost middle of test; early portion closely coiled, with four triangular chambers, well-marked, gradually enlarging with growth; later portion uncoiled with four low and broad chambers, distinct, enlarging gradually as added, last two chambers increasing rather rapidly in width; sutures in early portion more or less distinct, somewhat thickened and depressed, gently curved; sutures in later portion distinct, thickened, depressed, curved, oblique to axis; periphery lobulate; aperture radiate, at dorsal angle; wall calcareous; surface smooth.

Dimensions (in mm): Length 0. 34, maximum width 0.21, thickness 0.06.

Remarks: A solitary and well-preserved specimen of *Vaginulinopsis* which could not be compared with any known species of the genus was recovered from the present material. Perhaps, it represents a new species but more specimens are required before a trivial name could be assigned to it.

Occurrence: Rare

Repository of type material: AMUGD Cat. No. 526

Superfamily VAGININULININAE Reuss, 1860

Genus CITHARINA d'orbigny, 1839

***Citharina clathrata* (Terquem)**

Plate II, Figure 24

Marginulina longuemari var. *clathrata* TERQUEM, 1864, p. 402, pl. 8, fig.16, 19 a, b.

Citharina clathrata (Terquem) – BHALLA and ABBAS, 1978, pp. 176-177, pl. 5, fig. 8; pl. 9, fig. 1-5, *et syn.* – BHALLA and TALIB, 1991, p. 97, pl.II, fig. 2, *et syn.*

Description: Test medium, elongated, maximum width approximately at the middle of test, compressed to slightly inflated, flaring, triangular in outline; chambers well-marked, seven in number, following globular proloculus, enlarging rapidly in width but gradually in height as added, later chamber very low and broad; sutures distinct, thickened, flush with surface, gently curved, sub-parallel except in early portion, oblique to axis; periphery entire, sometimes very slightly lobulate in later part of test, keeled; apertural margin straight to gently curved; peripheral margin convex; apearture radiate, at dorsal angle; wall calcareous; surface ornamented with six longitudinal costae, running along entire length of test except proloculus, sometime bifurcating, uninterrupted by sutures.

Dimensions (in mm): Length 0. 17 to 0.28, width 0.14 to 0.16, thickness 0.05 to 0.08.

Remarks: Some specimens of *Citharina clathrata* (Terquem) were found in the present material. Bhalla and Abbas (1978) described it from the Jurassic rocks of Kachchh and worked out its variation and dimorphism. These authors noted that *C. pseudolatissima* reported by Subbotina and Datta (in Subbotina *et al.*; 1960) from the Jurassic of Kachchh is similar to *C. Clathrata* in all respects and that the former should be treated as a junior synonym of *C. Clathrata.* Our specimen bears close resemblance with the forms described by Bhalla and Abbas (1978), Bhalla and Talib (1991) and also those described by Subbotina and Datta (*op cit.*).

***Citharina hetroplura* (Terquem)**

Plate II, Figure 25

Marginulina hetroplura TERQUEM, 1868, p.116, pl. 7, figs.19-25.

Citharina hetroplura (Terquem) – BHALLA and ABBAS, 1978, p.177, pl. 5, fig.9; pl. 9, figs.6-10, *et syn.* – BHALLA and TALIB, 1991, p. 98, pl. II, fig.3, *et syn.*

Description: Test large, elongate, flattened sub-triangular, greatest width at lower part of test; chambers distinct, six in number, enlarging more in width but little in height as added; sutures distinct, rather thick, slightly depressed; periphery entire, keeled; apertural margin gently curved, peripheral margin convex; apearture rather indistinct, appears to be radiate, at peripheral angle; wall calcareous; surface ornamented with ten longitudinal costae, running along the entire length of test.

Dimensions (in mm): Length 0.36, width 0.14, thickness 0.06.

Remarks: A solitary specimen of *Citharina hetropleura* (Terquem) was recorded from the present material. Our from is somewhat similar to those described by Bhalla and Abbas (1978) as well as Bhalla and Talib (1991) from Habo and Jhurio hills respectively, but in the present specimen chambers are not strongly drawn towards proloculus as in the forms described by these authors. The Indian forms are also identical with *Citharina hetropleura* (Terquem) described by Cifelli (1959) from Bathonian of England.

Occurrence: Rare

Repository of type material: AMUGD Cat. No. MF. 528

Genus CITHARINELLA Marie, 1938

***Citharinella* aff. *C. compara* Loeblich and Tappan**

Plate II, Figure 26

aff. *Citharinella compara* LOEBLICH and TAPPAN, 1950 b, p. 14-15, pl. 1, fig. 36a, b; text - fig. 3A-D.

aff. *Citharinella compara* (Loeblich and Tappan) – BHALLA and TALIB, 1991, p. 98, pl. II, fig.11, *et syn.*

Description: Test medium, lanceolate, flattened; early portion *Citharine,* oval proloculous followed by four low and broad triangular chambers, enlarging gradually as added; later portion *Frondicularine*, with five cheveron-shaped chambers, enlarging little in height and width as added; sutures distinct, thin, slightly raised, gently curved in early portion, acutely arched upwards in later part; periphery slightly labulate; apeartural end broken; wall calcareous; surface smooth.

Dimensions (in mm): Length 0.26, breadth 0.10, thickness 0.03.

Remarks: A single specimen of *Citharinella* with broken apertural end was recovered from present material. It shows affinity to *C. Compara* originally described by Loeblich and Tappan (1950b) from the Callovian of North America. From the Kachchh region, Bhalla and Talib (1991) reported this species from Callovian-Oxfordian of Jhurio hill. However, our form possesses unornamented test and slightly raised sutures.

Occurrence: Rare

Repository of type material: AMUGD Cat. No. MF. 529

Suborder ROBERTININA Loeblich and Tappan, 1984

Superfamily CERATOBULIMINACEA Cushman, 1927

Family EPISTOMINIDAE Wedekind, 1937

Subfamily EPISTOMININAE Wedekind, 1937

Genus EPISTOMINA Terquem, 1883

***Epistomina hechti* Bartenstein, Bettenstaedt and Bolli**

Plate II, Figure 27

Epistomina hechti BARTENSTEIN, BETTENSTAEDT and BOLLI, 1957, p.46, figs.17a-c.

Epistomina hechti (Bartenstein, Bettenstaedt and Bolli) - WILLIAMSON and STAM, 1988, p.140, pl. 3, figs 6,7.

Description: Test medium, biconvex, nearly circular to oval in outline, trochospiral, closely coiled, more strongly convex ventrally; chambers of dorsal side well-marked, about eight in last whorl, trapezoid in shape, increasing gradually as added; chambers of ventral side triangular, enlarging progressively as added; dorsal sutures distinct, limbate, raised, curved, making strong reticulation in central part; ventral sutures distinct, limate, radiate, raised, nearly straight to somewhat curved, running upto a central umbilical area; umbilical area small with minute reticulation; periphery fairly lobulate, distinctly carinate, with a week secondary keel, aperture indistinct; wall aragonitic; surface smooth.

Diamensions (in mm): Major diameter 0.18, thickness 0.11.

Remarks: A solitary specimen of *Epistomina* was found in present material which show close resemblance with *Epistomina hechti* (Bartenstein, Bettenstaedt and

Bolli, 1957) described and illustrated by Williamson and Stam (1988) from Canada and Europe. *Epistomina hechti* is characterised by the presence of radiate sutures running upto central umbilical area and having small umbilicus with minute reticulation. Our specimen is also similar to those figured by Williamson (1987).

Occurrence: Rare

Repository of type material: AMUGD Cat. No. 530

***Epistomina mosquensis* Uhlig**

Plate II, Figure 28

Epistomina mosquensis UHLIG, 1883, p.776, pl.7, fig.1-3

Epistomina mosquensis (Uhlig) – WILLIAMSON and STAM,1988, p.142, pl.1, figs 2,3; – BHALLA and TALIB, 1991, p.104-105, pl.IV, fig.19, *et syn.*

Description: Test medium, biconvex, nearly circular to oval in outline, trochospiral, closely coiled, more strongly convex dorsally; chambers of dorsal side well-marked, about eight in last whorl, trapezoid to triangular in shape, increasing gradually as added; chambers of ventral side triangular, enlarging progressively as added; dorsal sutures distinct, limbate, raised, curved, making reticulate pattern on initial whorl; ventral sutures distinct, limbate, radiate, raised, nearly straight, forming a sharp raised umbilical collar with central depression; periphery fairly lobulate, distinctly keeled; aperture indistinct; wall aragonitic; surface smooth.

Dimensions (in mm): Major diameter 0.13 to 0.18, thickness 0.08 to 0.10.

Remarks: The specimen of *Epistomina* though rather poorly preserved but strongly resembling with *Epistomina mosquensis* Uhlig, 1883, was obtained from the present material. Our form exhibit close similarity to those described and figured by Williamson and Stam (1988) from Jurassic of Canada and Europe as well as Bhalla and Talib (1991) from Jhurio hill, Kachchh. *Epistomina mosquensis* Uhlig is characterised by presence of straight radiate sutures and a high sharp umbilicul collar surrounding a central depression on the ventral side of the test.

Occurrence: Rare

Repository of type material: AMUGD Cat. No. MF. 531

***Epistomina omninoreticulata* Espitalie and Sigal**

Plate II, Figure 29

Epistomina omninoreticulata ESPITALIE and SIGAL, 1963 pl.31, figs.7a-f.

Epistomina omninoreticulata (Espitalie and Sigal) – WILLIAMSON and STAM, 1988, p.142, pl. 4, figs. 4, 5.

Description: Test medium, biconvex, nearly circular to oval in outline, trochospiral, closely coiled, more strongly convex dorsally; chambers of dorsal side well-marked, about eight in last whorl, trapezoid in shape, increasing gradually as added; chambers of ventral side triangular, enlarging progressively as added; dorsal sutures distinct, limbate, raised, curved, obscured by strong reticulate pattern; ventral sutures distinct, limbate, raised, nearly straight to somewhat curved, umbonal area covered with reticulate pattern; periphery fairly lobulate, distinctly keeled; aperture indistinct; wall aragonitic; surface smooth.

Dimensions (in mm): Major diameter 0.24, thickness 0.13

Remarks: A single specimen of *Epistomina omninoreticulata* Espitalie and Sigal, 1963, was recovered from present material. Our form closely resembles to those described by Williamson and Stam (1988) from Canada and Europe. Presence of well-developed reticulation on both side of the test covering large areas, often obscuring sutures on the dorsal side, are the distinguishing features of this species.

Occurrence: Rare

Repository of type material: AMUGD Cat. No. MF. 532

***Epistomina* aff. *E. prerjasanesis* Pandey and Dave**

Plate II, Figure 30

Epistomina prerjasanesis PANDEY and DAVE, 1993, pp.144-145, pl.17, figs. 7, 9; pl. 18, figs. 1-4, *et syn.*

Description: Test small, biconvex, nearly circular to oval in outline, trochospiral, closely coiled, more strongly convex dorsally; chambers of dorsal side well-marked, about six in last whorl, trapezoid to triangular in shape, increasing gradually as added; chambers of ventral side triangular, enlarging progressively as added; dorsal sutures distinct, thin, moderately raised, curved, making coarse reticulation in spire; ventral sutures distinct, flushed with surface, nearly straight, forming slightly raised umbilical area; periphery fairly lobulate, distinctly keeled; apearture indistinct; wall aragonitic; surface smooth.

Dimensions (in mm): Major diameter 0.14, thickness 0.07.

Remarks: A solitary specimen of *Epistomina* which shows affinity with *E. prerjasanesis* (Pandey and Dave) was encounted in our material. *Epistomina prerjasanesis* was first described by Pandey and Dave (1993) from Jurassic sediments of Kachchh and is characterised by the presence of plano-convex test, coarse reticulation on dorsal side, and slightly raised umbilical area on ventral side of the test. Our form differs in having a rather biconvex test.

Occurrence: Rare

Repository of type material: AMUGD Cat. No. MF. 533

***Epistomina regularis* Terquem**

Plate II, Figure 31

Epistomina regularis TERQUEM, 1883, pl. 44, figs. 1a-c, 2, 3.

Epistomina regularis (Terquem) – WILLIAMSON and STAM, 1988, p.144, pl. 4, figs.7-9; – PANDEY and DAVE, 1993, p. 148, pl.10, figs. 6-7, pl. 11, figs.1-3.

Description: Test medium, biconvex, nearly circular to oval in outline, trochospiral, closely coiled, more strongly convex dorsally; chambers of dorsal side well-marked, about eight in last whorl, trapezoid to triangular in shape, enlarging gradually as added; chambers of ventral side triangular; enlarging progressively as added; dorsal sutures distinct, thin, moderately raised, curved, making reticulate pattern on initial whorl; ventral sutures distinct, limbate, raised, nearly straight, form minute rough irregular reticulate pattern, covering large area; periphery fairly lobulate, distinctly keeled; apearture indistinct; wall aragonitic; surface smooth.

Dimensions (in mm): Major diameter 0.16 to 0.22, thickness 0.08 to 0.13.

Remarks: A specimen of *Epistomina regularis* Terquem, 1883 extracted from the Kachchh material is comparatively well preserved and closely resemble the form described by Williamson and Stam (1988) from Canada and Europe. *E. regularis* is similar to *E. mosquensis* but differs in having rough irregular reticulate pattern which cover large area on the central part of ventral side of the test. Our form is also similar to those recorded by Pandey and Dave (1993) from Jurassic of Kachchh.

Occurrence: Rare

Repository of type material: AMUGD Cat. No. MF. 534

Epistomina tenuicostata **Bartenstein and Brand**

Plate II, Figure 32

Epistomina tenuicostata BARTENSTEIN and BRAND, 1951, p. 327, pl. 12, fig. 325.

Epistomina tenuicostata (Bartenstein and Brand) – WILLIAMSON and STAM, 1988, p.146, pl. 4, figs. 3, 6.

Description: Test medium, biconvex, nearly circular, trochospiral, closely coiled, gently convex dorsally; chambers of dorsal side well-marked, about eight in number, trapeozoid, enlarging gradually as added; chambers of ventral side triangular in shape enlarging progressively as added, last chamber often slightly overlaps the umbilicus; dorsal sutures distinct, limbate, raised, curved, making reticulate pattern near umbilical area; ventral sutures distinct, limbate, radiate, slightly raised, nearly straight to gently curved towards periphery, forming an umbilical ring; periphery fairly lobulate, distinctly keeled; apearture indistinct; wall aragonitic; surface smooth.

Dimensions (in mm): Major diameter 0.22, thickness 0.10.

Remarks: A solitary specimen of *Epistomina tenuicostata* (Bartenstein and Brand) was recovered in the present material. The main distinctive feature of this species is the nature of last chamber on ventral side, overlapping as it does part of the umbilical area. Our form is similar to those described by Williamson and Stam (1988) and Williamson (1987).

Occurrence: Rare

Repository of type material: AMUGD Cat. No. MF. 35

***Epistomina* sp. indet.**

Plate II, Figure 33

Description: Test medium, biconvex, nearly circular in outline, trochospiral, closely coiled, slightly more convex dorsally; chambers of dorsal side well-marked, about seven in last whorl, trapezoid in shape, increasing gradually as added; chambers of ventral side triangular, enlarging progressively as added; dorsal sutures distinct, thin, slightly raised, somewhat curved, forming reticulated umbilicus in central part; ventral sutures distinct, thin, slightly raised, somewhat straight, forming a small boss in umbilical area; periphery fairly lobulate, distinctly keeled; aperture indistinct; wall aragonitic; surface smooth.

Dimensions (in mm): Major diameter 0.15, thickness 0.06.

Remarks: A single but well preserved specimen of *Epistomina,* possibly of a new species was recovered from the present material which could not be compared with any known species of the genus.

Occurrence: Rare

Repository of type material: AMUGD Cat. No. MF. 536

CHAPTER 5

COMPOSITION AND PALAEOECOLOGY OF THE FORAMINIFERAL ASSEMBLAGE

COMPOSITION OF THE FORAMINIFERAL ASSEMBLAGE

A foraminiferal assemblage comprising thirty-three species has been recovered from the Jurassic sediments exposed at Keera hill, Kachchh. The following four species are being described for the first time from Kachchh region: *Reophax* aff. *R. suevica, Ammobaculite nanogyrus, Lenticulina ectypa, Epistomina hechti, Epistomina omninoreticulata.* The foraminiferal assemblage also includes three indeterminate species one each belonging to *Lenticulina, Vaginulinopsis* and *Epistomina* which do not show resemblance to any known species of these genera. These are probably new species but more specimens are required to assign them new trivial names.

The present foraminiferal assemblage is dominated by the family Vaginulinidae, constituting 54.54% of the total fauna (Figure 5). It comprises eighteen species belonging to eight genera, i.e., *Lenticulina, Sarcenaria, Astacolus, Hemirobulina, Marginulina, Vaginulinopsis, Citharina and Citharinella.* The family Epistominidae is represented by seven species belonging to genus Epistomina and constituting 21.22% of the total population. Family Nodosariidae includes three species with three genera i.e. *Nodosaria, Pyramidulina,* and *Frondicularia.* Family Lituolidae is represented by two species of the genus *Ammobaculites.* These two families comprising 9.09% and 6.06% of the whole foraminiferal assemblage respectively. Other families in the present assemblage are Hormosinidae, Involutinidae and Spirillinidae which are represented by solitary species belonging to genera *Reophax, Trocholina* and *Spirillina,* respectively, each of them forming 3.03% of the entire foraminiferal population (Figure 6).

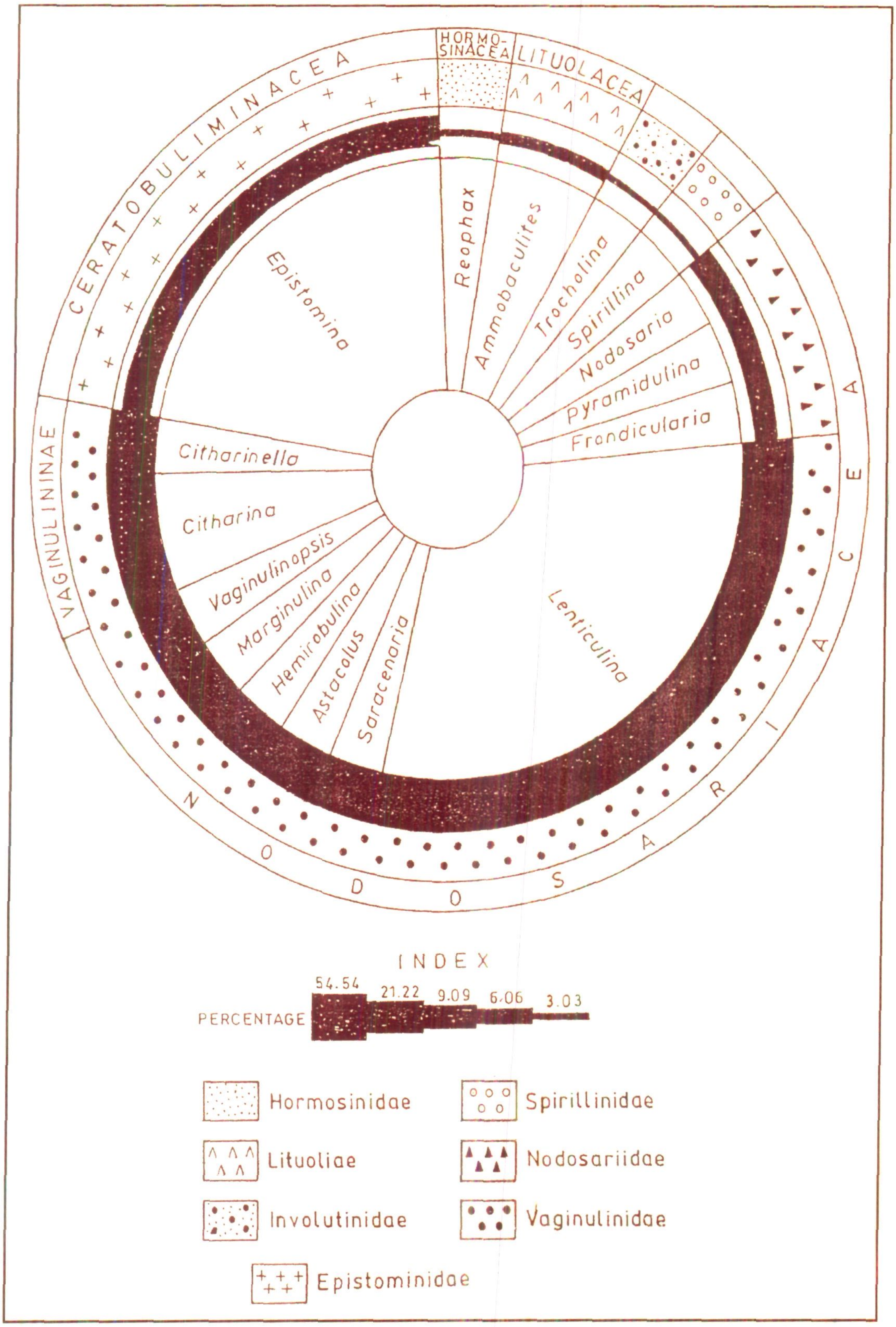


Figure 5: Composition of foraminiferal assemblage, Keera hill, Kachchh

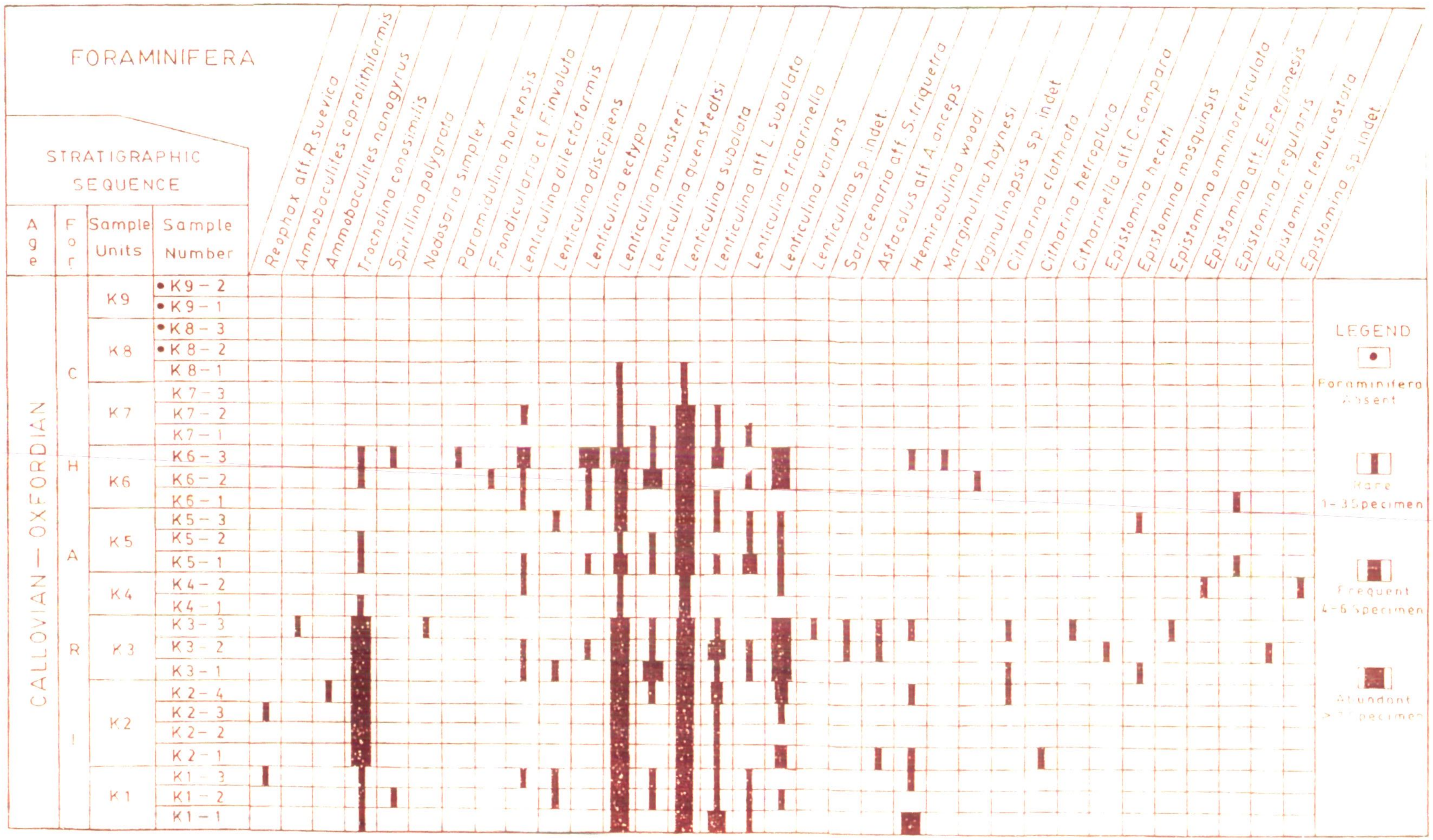


Figure 6: Frequency distribution of foraminifera in the Jurassic sequence at Keera hill, Kachchh

The Keera hill assemblage also contains a few species of post-Jurassic foraminifera belonging to genera *Cibicides, Nonion, Ammonia* and *Elphidium.* These are represented by a small number of specimens, which are worn out with obliterated morphological features and frosted surfaces and with well rounded shape. On the other hand, the Jurassic foraminifera are abundant, well preserved and clearly show the morphological features.

Post-Jurassic foraminiferal elements have also been recorded by various workers on Kachchh Mesozoic. The presence of Tertiary element, e.g. *Elphidium,* in the Jurassic rocks of Kachchh has been observed by Agrawal and Singh (1960). But they did not provide any explanation for this unusual occurrence. Bhalla and Talib (1978) reported thirteen and nine post-Jurassic foraminiferal genera from Habo and Jhurio hills, Kachchh, respectively. These authors (*op.cit*) suggested that the post-Jurassic foraminiferal species were brought in by the westerly winds and dust storms from the western and northwestern parts of the region, where marine Tertiary sediments and Recent beach sands are well exposed, and sprayed over the Jurassic exposures. Thereafter, they impregnated the Jurassic exposures through percolating water during monsoon season and got entombed in these sediments.

As discussed earlier, the post-Jurassic foraminifera of the present assemblage show rounded outline, obliterated morphological features and abraded surfaces, these being the characters of wind-borne sediments. Hence, these are not included in the present study, as they are not considered indigenous.

FORAMINIFERAL PALAEOECOLOGY AND PALAEOENVIRONMENT

Foraminifers are widely known to be reliable indicators of the environment in which they live. Due to their extreme sensitiveness to the environment and abundance through major portions of the geological column, foraminifera provide valuable tool to interpret past environments at least as far back as Cretaceous (Sliter and Baker, 1972; Murray, 1991; Gebhardt, 1998) and in many cases even up to Jurassic (Barnard and Shipp, 1981; Bhalla and Abbas, 1984; Bhalla and Talib, 1991; Gebhardt, 1998;

Talib and Gaur, 2005). However, when applying Cretaceous and older foraminifera to deduce past environments, interpretations should not be based solely on comparison with modern environments and their fauna, as certain group of foraminifera have changed their environmental preferences through time. Working on ecology and palaeoecology of foraminifera, several authors (Natland, 1957; Skolnick, 1958, Phleger, 1960; Burnaby, 1962; Ager, 1963) observed that with the commencement of Palaeogene Period some groups of foraminifera have changed their habitat and caution must be observed while interpreting palaeoenvironments based on pre-Palaeogene assemblages.

Few workers (Said, 1950; Wall, 1960) consider that ecological studies should be based on individual foraminiferal species rather than genera or families as different species of a genus may thrive in a wider range of environment and, therefore, the palaeoecological interpretation based on genera and families are rather unreliable. However, it is also true that palaeoecological interpretations solely based on individual species is not reliable, especially in the pre-Cretaceous sediments because certain foraminiferal species occurring in older rocks may represent entirely different environmental conditions as compared to their modern counterparts (Phelger, 1960). However, various workers (Shipp and Murray, 1981; Bhalla and Abbas, 1984; Gebhardt, 1998; Bhalla and Talib, 1991; Nagy and Seidenkrantz, 2003; Talib and Gaur, 2005) interpreted the palaeodepositional environments of the pre-Cretaceous rocks based on foraminiferal genera and families because most of the foraminiferal species of this age do not exist in the modern time.

Jurassic foraminiferal assemblages are usually dominated by the families Vaginulinidae and Nodosariidae and both have unequivocally changed their habitat from shallow to deeper waters from Palaeogene onwards (Barnard, 1948; Bhalla and Abbas, 1978; Coleman, 1981; Bhalla and Talib, 1991; Talib and Gaur, 2005). Furthermore, extreme variation exhibited by these families creates problems in their identification and consequently in drawing paleoecological interpretations.

However, in spite of all these constraints several recently developed techniques are being successfully used to draw fairly accurate palaeoecological interpretations based on foraminiferal assemblages. Few of the important and widely used methods are briefly discussed here.

METHODS OF PALAEOECOLOGICAL INTERPRETATIONS

The following methods are usually used in the palaeoecological studies using foraminifera:

1. Diversity Indices (Fisher–index)
2. Triangular plot of foraminiferal test structure
3. Planktic - benthic (P/B) ratio
4. Tolerance of taxa (mainly at generic level) with respect to some environmental parameters (bathymetry, temperature, salinity levels, calcium carbonate availability, dissolved oxygen levels, substrate conditions, water energy).
5. Occurrence of dominant species in relation to species diversity.
6. Morphogroups

Diversity indices (Fisher's α Index)

Several diversity indices are available but the most commonly used for foraminiferal studies is Fisher's α index which was introduced by Fisher *et al.* (1943, in Murray, 1991). It takes into account the number of species among a certain number of specimens.

$$\alpha = n_1 : x$$

where x is a constant having values < 1, $n_1 = N(1\text{-}x)$, N being the number of individual. Low values of α suggest some deviation from normal environmental parameters. However, it should be kept in mind that the species diversity in fossil assemblages could be influenced by taxonomical processes.

Triangular Plot for the Foraminiferal Test Structure

It is based on three types of foraminiferal test wall: agglutinated, porcellaneous, and hyaline, corresponding with three suborders – Textulariina, Miliolina, and Rotaliina from the Loeblich and Tappan's (1964) classification. However, in the revised classification (Loeblich & Tappan, 1988) suborder Rotaliina is divided into four suborders – Spirillinina, Lagenina, Robertinina, and Rotaliina.

Planktic/Benthic ratio

With the increase of depth the percent abundance of planktic individuals also increases. However, there are exceptions – very wide shelves and enclosed epicontinental seas are characterized by low abundance of planktic forms despite the depth. With the approach of carbonate compensation depth (CCD – 3500-4000m) a gradual dissolution of the calcareous tests is observed, and below this planktic forms are not available.

Tau-index was introduced as bathymetrical indicator by Gibson (1988) based on data obtained from the Gulf of Mexico. It could be calculated using the formula

$$\text{tau} = b \,.\, \%p$$

Where b is the number of benthic species, and p the number of planktic individuals in a sample. With the increase of depth the values of tau increase.

Tolerance of Taxa With Respect To Some Environmental Parameters

Particular taxa demonstrate different tolerance of depth, temperature, salinity, aeration, calcium carbonate and silica availability, water energy, and substrate conditions. Of great importance are taxa with minimal tolerance of changes in the above mentioned parameters. Data from modern assemblages, as well as data obtained during the deep sea drilling in the Atlantic, Pacific, and Indian oceans are used in the interpretation.

Occurrence of Dominant Species In Relation To Species Diversity

The strong dominance of some species in relation to low species diversity suggests deviation from the norm of some of the parameters. The absence of dominant species in relation to high species diversity indicates stable environmental parameters.

MORPHOGROUPS

Based on the external morphology, the benthic foraminiferal population can be clubbed into two coarser morphogroups namely, angular-asymmetrical and rounded-symmetrical. The distribution profiles of these morphogroups in the surface sediments apparently showed that angular-asymmetrical group is more or less abundant in deeper regions while rounded-symmetrical morphogroup tends to flourish in relatively shallower regions. Such characteristic pattern indicates depth control over the external morphology of benthic foraminifera. Therefore, if these morphogroups are studied in ancient sediments, they may show great potential in generating proxy data for palaeo-depth.

The significance of morphogroups was initially recognized by Chammy(1976), Severin (1983), Jones and Charnock(1985), and Bernhard (1986). Studies of modern and ancient foraminiferal assemblages demonstrate that the morphology of the foraminiferal test (mode of coiling, chamber arrangement, features of aperture, position of perforation) can be directly related to different life styles and trophic strategies (Corliss, 1985, 1991; Nagy, 1992; Tyszka, 1994 and others). According to Nagy (1992), the use of morphological categories in the palaeoenviromental analyses, rather than species, is advantageous because:

1) The morphogroup approach allows reliable comparisons of assemblages. Belonging to different ages, reducing the effect of taxonomic divergences caused by biological evolution

2) Taxonomical determinations at the species level are not required

3) This approach simplifies analyses by reducing number of variables (as opposed to use of species)

Reolid *et al.* (2008) identified eleven morphogroups (A-K) differentiated according to test composition, general morphology, number of chambers and mode of coiling and some of them were subdivided into subgroups. Their relations to previously proposed morphological units were also outlined. The agglutinated and calcareous foraminifera were treated separately and arranged in separate morphogroup sets. Following previous interpretations, morphogroup developments were primarily attributed to lifestyle and secondly to feeding strategies. The morphogroup scheme of Reolid *et al.* (2008) is being followed in the present study. The morphograph scheme of the (Reolid *et al.* 2008) of Keera hill foraminiferal assemblage displayed in Table 2.

FOR AMINIFERAL PALAEOECOLOGY OF CHARI SEQUENCE EXPOSED AT KEERA HILL

The Keera hill foraminiferal assemblage includes an overwhelming majority of the species belonging to the family Vaginulinidae. Only calcareous hyaline and agglutinated forms are present in the present foraminiferal assemblage. Porcellaneous species are conspicuously absent from the Keera hill foraminiferal assemblage.

A survey of relevant literature indicated that the depth distribution of vaginulinids is debatable. Some researchers (Norton, 1930, Natland, 1933; Glaessner, 1945) have suggested a moderately deep marine environment for this group while others (Barnard, 1948; Brouwer, 1969) interpreted a shallow-marine environment. However, many workers opined that this group appears to have changed its habitat from near shore shallow marine water in the Mesozoic to deep water from Palaeogene onwards but always preferring open marine environment with normal salinity (Bhalla and Abbas, 1978; Bhalla and Talib, 1980, 1991). The high percentage of vaginulinids in the Keera hill foraminiferal assemblage points towards a shallow water open marine environment, most probably the deeper parts of the shelf. As the present assemblage contains only calcareous hyaline and agglutinated species and porcellanous forms are absent (Figure 7A), it may be inferred that the Keera hill foraminiferal assemblage was thriving in the mid and outer shelf regions with normal salinity. The high fisher index value of 12.44 for the entire assemblage provides additional support for this view, suggesting a relatively deep shelf sea, most probably in the mid to outer shelf region with normal salinity and oxygen level. Abundance of genus *Epistomina* (included in morphogroup G of Reolid *et al.*, 2008) also points towards an outer shelf environment in the sub-tidal zone (Bernier, 1984; Meyer, 2000; Samson, 2001). Dominance of hyaline foraminifers in the Keera hill assemblage points towards normal salinity conditions, also supported by a high Fisher index value of >5 for the entire assemblage (Murray, 1991). Higher alpha index (>5) and dominance of infaunal genus *Lenticulina* suggests normal oxygen level, *Lenticulina* being the most abundant genus in the present assemblage (Figure 7B).

The Keera hill foraminiferal assemblage exhibits the dominance of morphogroups K of Reolid *et al.* (2008) (Figure 7C). Morphogroup K includes biconvex (lenticular), planispiral multilocular forms. This micrphogroup, represented by *Lenticulina* is adapted to epifaunal to deep infaunal microhabitats and active deposit feeder and grazing omnivore feeding habits (Reolid *et al,* 2008). Diverse Lenticulina assemblages are indicative of high level of dissolved oxygen (Bernhard, 1986; Koutsoukos *et al.* 1990). The above discussion reveals that the foraminiferal assemblage recovered from the Chari sequence at Keera hill, Kachchh supports an open marine environment of mid to outer shelf, having normal salinity and high dissolved oxygen level.

However, in order to trace the finer and more subtle palaeoenvironmental fluctuations during the deposition of the Chari sequence of Keera hill, some of the above mentioned palaeoecological methods using foraminifera were employed. For this purpose, Fisher index (calculated using PAST software) was first applied for interpreting bathymetric changes during the deposition of the Keera hill sequence (Figure 8A). Thereafter, fisher index, agglutinated/calcareous ratio, morphogroups after Reolid *et al.* (2008) (Figure 8B), and dominance of certain palaeoecologically significant taxa were employed to interpret some of the palaeoecological variables including depth, salinity, and oxygen level. This facilitated in dividing the sequence in to ten palaeoecological units representing fluctuations in bathymetric and palaeoenvironmental conditions during the deposition of the Chari sequence exposed at Keera hill, Kachchh. The palaeobathymetry and palaeoecology of each one of these units is discussed below in considerable detail:

Table 2: Benthic foraminiferal morphogroups (Reolid *et al.* 2008) in the Jurassic succession of Keera hill, Kachchh.

MORPHO GROUP			TEST FORM	LIFE - STYLE	FEEDING STRATEGY	EXAMPLES
AGGLUTINATEDS	A		Tubular and Unilocular	Epifaunal	Suspension feeders	NILL
	B		Plano-convex irregular	Sessile epifaunal	Passive herbivores (suspension feeders?)	NILL
	C	C1	Elongated uniserial	Shallow to Deep infaunal	Detrivores bacterial scavangers	*Reophax*
		C2	Elongated uniserial,initial coiled phase	Shallow infaunal	Detrivores bacterial scavangers	*Ammobaculites*
		C3	Elongated biserial,triserial and high trochospiral	Shallow to Deep infaunal	Detrivores bacterial scavangers	*NILL*
	D		Rounded ,globular and plano-convex planispiral to low trochospiral	Epifaunal	Active herbivores,omnivores,detrivores and bacterivores	NILL
	E		Discoidal coiled(unilocular)	Epifaunal (phytal)	Active herbivores,detrivores	NILL
CALCAREOUS	F		Plano-convex and meandering initial phase coiled	Sessile Epifaunal	Passive herbivores (suspension feeders?)	NILL
	G		Plano-convex trochospiral	Epifaunal	Primary weed fauna grazing herbivores	*Epistomina*
	H		Discoidal flattened(planispiral) and plano-convex(trochospiral)	Epifaunal	Primary weed fauna grazing herbivores/phytodetrivores	*Spirillina, Trocholina*
	I		Discoidal flattened spiral, elongated	Epifaunal	Active deposit- feeders herbivores,detrivores	NILL
	J	J1	Elongated uniserial	Shallow infaunal	Active deposit feeders,herbivores,bacterial scavengers	*Nodosaria, Marginulina, Pyramidulina, Hemirobulina*
		J2	Elongated flattened	Shallow infaunal	Active deposit- feeders grazing omnivores	*Frondicularia, Saracenaria, Astacolus, Vaginulinopsis, Citharina, Citharinella,*
	K		Biconvex (lenticular) planispiral	Epifaunal to deep infaunal	Active deposit-feeders,grazing omnivores	*Lenticulina*

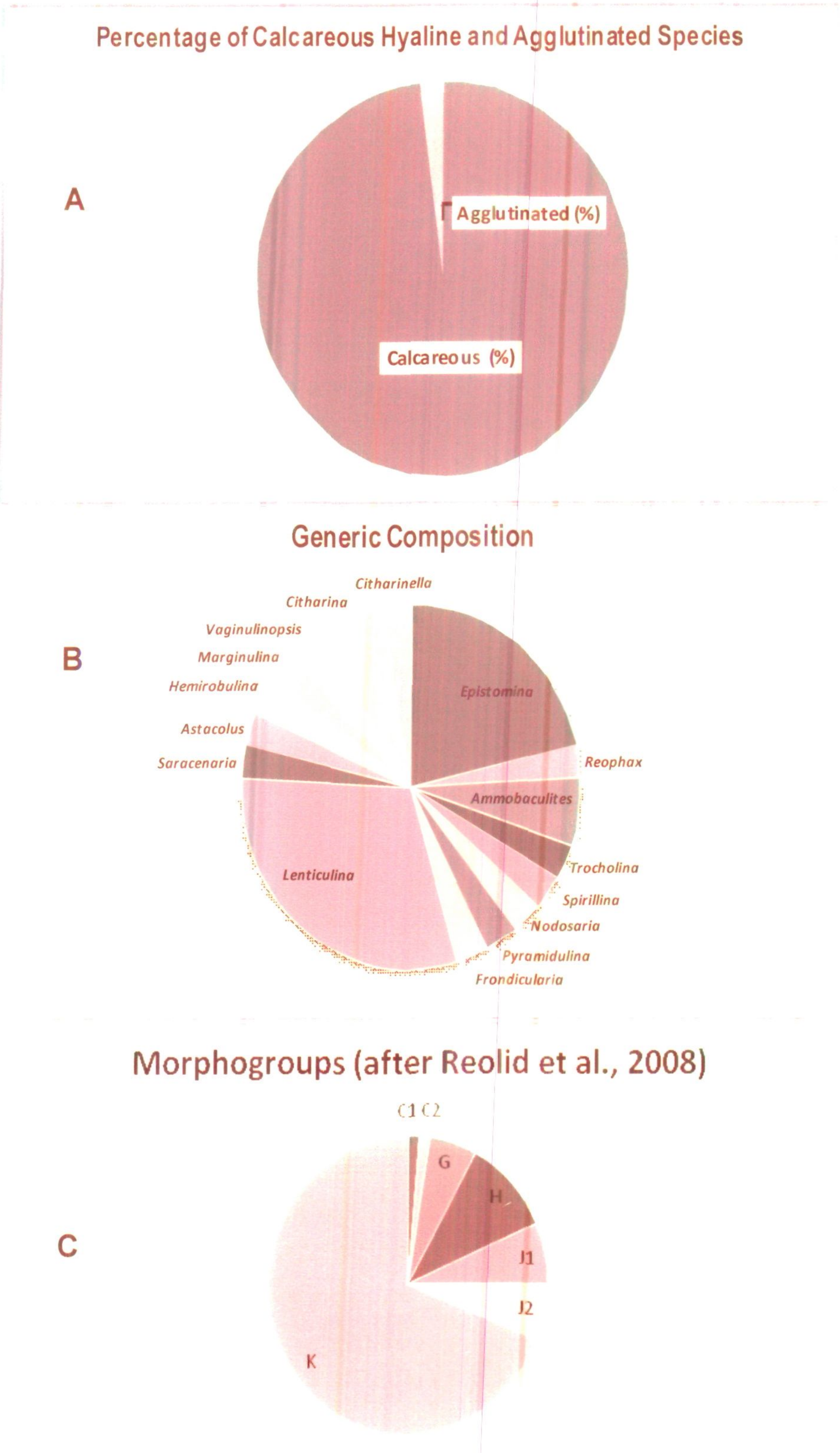
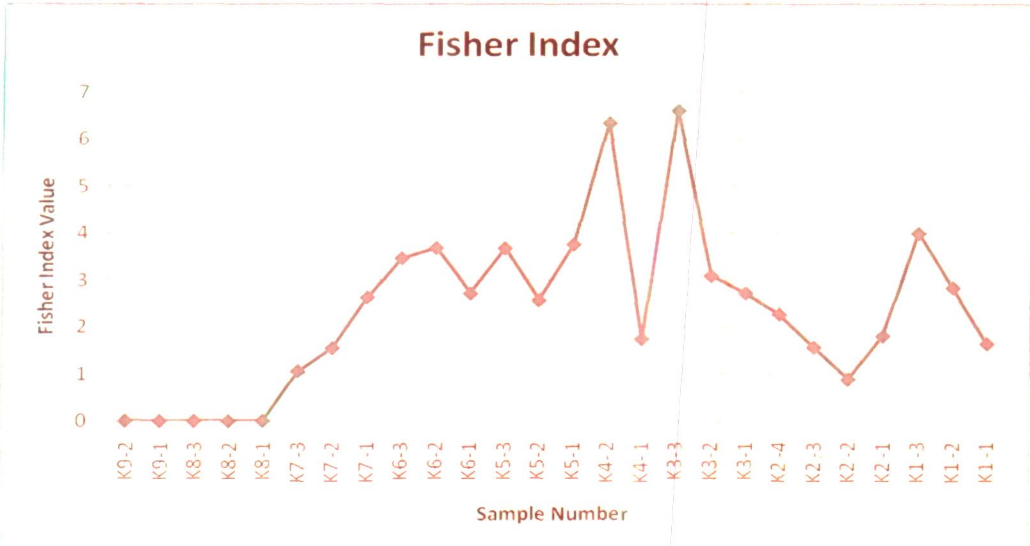


Figure 7: Characters of the foraminiferal assemblage, Keera Hill, Kachchh.



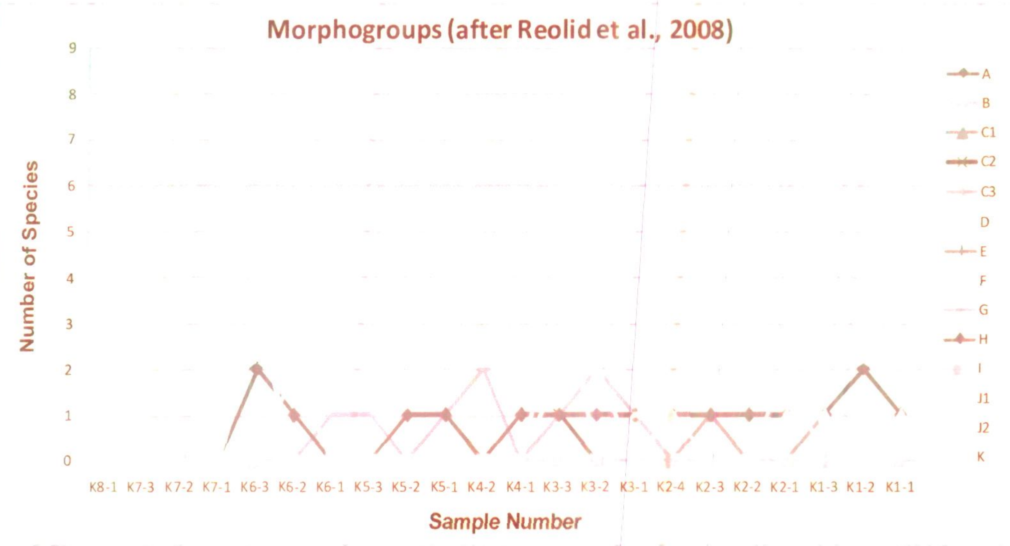


Figure 8: Variation in various attributes of the foraminiferal assemblage throughout Callovian-Oxfordian Sequence, Keera Hill, Kachchh.

Palaeoecological Unit I (samples K1-1 to K1-3)

The first palaeoecological unit of the Chari sequence exposed at Keera Hill, Kachchh comprises lithounits K1. The maximum Fisher index value of this unit is 3.89, considerably higher than the succeeding unit, indicating deposition in relatively deep conditions within the shelf, most probably the outer shelf region. Overwhelming majority of the calcareous hyaline component suggests normal salinity conditions. Dominant morphogroup in this unit is K suggesting high dissolved oxygen level.

The Palaeoecological Unit I appear to have deposited in outer shelf region with normal salinity and high oxygen level.

Palaeoecological Unit II (samples K2-1 to K3-2)

This palaeoecological unit includes Lithounit K2 and lower portion of Lithounit K3. The Fisher index value is considerably low, maximum being 3.09, suggesting a mid shelf environment. Dominance of calcareous forms suggests normal salinity conditions and good oxygen level is indicated by dominance of morphogroup K.

The sediments belonging to Paleoecological Unit II seems to have deposited in shallower shelf settings in the region of mid shelf with normal salinity and high level of dissolved oxygen.

Palaeoecological Unit III (sample K3-3)

This palaeoecological unit comprises a single sample comprising upper part of Lithounit K3. The Fisher index is highest amounting to 6.59, indicating a transgressive phase in the deepest part of the outer shelf region. Dominance of calcareous hyaline species suggests normal salinity level. A high oxygen level is suggested by high fisher index value and dominance of morphogroup K in this unit indicates good oxygen level.

Palaeocological Unit III appears to have been deposited in the deepest part of the outer shelf with normal salinity and good oxygen level.

Palaeoecological Unit IV (sample K4-1)

This palaeoecological unit includes a single sample of the lower part of Lithounit K4. There is a substantial lowering of the Fisher index to 1.74, suggesting shallowing of the depositional site to mid-shelf region. Presence of only calcareous hyaline forms suggests normal salinity and dominance of morphogroup K indicates well oxygenated environment.

This palaeoecological unit represents a shallower shelf environment in the mid shelf region, slightly deeper than in unit II, with normal salinity and well oxygenated environment.

Palaeoecological Unit V (samples K4-2 and K5-1)

Palaeoecological Unit V encompasses the Upper part of Lithounit 4 and lower portion of Lithounit 5. The Fisher index is substantially increased than the previous unit with a maximum of 6.33, indicating deepening of the depositional basin to outer shelf region. Presence of only calcareous species suggests normal saline condition which is also supported by the high value of Fisher index. Dominance of morphogroup K suggests well oxygenated water. Palaeoecological Unit V supports a considerably deep outer shelf environment, slightly shallower than unit III, with normal salinity as well as high oxygen level.

Palaeoecological Unit VI (sample K5-2)

It includes a single sample of the upper part of Lithounit K5. The Fisher index is reduced to 2.56 suggesting a minor regressive phase in the mid shelf region. Presence of only calcareous hyaline forms suggests normal salinity. Dominance of morphogroup K supports well oxygenated environment.

The sediments of this unit are presumed to have deposited in a shallow mid shelf environment but deeper than Units II and IV, with normal salinity and high level of dissolved oxygen.

Palaeoecological Unit VII (sample K5-3)

This palaeoecological unit encloses last sample of Lithounit K5. The Fisher index is higher than the previous unit reaching a maximum of 3.67, indicating a relatively deeper environment in the outer shelf, with the water depth being nearly the same as unit I but considerably shallower than units III and V. A normal salinity is interpreted in view of the presence of only calcareous hyaline forms. Dominance of morphogroup K suggests rich oxygen level.

This palaeoecological unit is interpreted to have deposited in a relatively deeper outer shelf environment with normal salinity and rich oxygen levels.

Palaeoecological Unit VIII (sample K6-1)

This palaeoecological unit of the Chari sequence exposed at Keera hill, Kachchh includes a single sample of the lower part of Lithounit K6. It displays a lowered Fisher Index value of 2.71, indicating a shallow mid shelf environment. Presence of only calcareous hyaline forms suggests normal salinity and a well oxygenated environment is inferred in view of the dominance of morphogroup K.

This palaeoecological unit is interpreted to have deposited in the shallow mid shelf region, with water depth nearly the same as unit VI, having normal salinity and well aerated environment.

Palaeoecological Unit IX (samples K6-2 and K6-3)

It includes the last two samples of Lithounit K6 and show an increase in the Fisher index with a maximum of 3.68, indicating deposition in outer shelf. Normal salinity is interpreted in view of presence of only calcareous hyaline forms. Dominance of morphogroup K suggests well oxygenated environment.

Sediments of Palaeoecological Unit IX are interpreted to have deposited in outer shelf with water depth equal to unit VII, having normal salinity and well oxygenated water.

Palaeoecological Unit X (samples K7-1 to K8-1)

The last palaeoecological unit of the Chari sequence exposed at Keera hill includes the entire Lithounit K7 and the lowermost sample of Lithounit 8, as rest of the samples are devoid of foraminifera. The Fisher index value is substantially lowered reaching up to 0 in sample K8-1 and highest being 2.62. This is interpreted as a regressive phase in the mid shelf region. Presence of only calcareous hyaline forms suggests normal salinity whereas well oxygenated environment is interpreted due to dominance of morphogroup K.

The last phase of deposition of the Chari sequence in the studied area took place in the shallowest mid shelf environment with gradual shallowing of the basin, where salinity was normal and the water was well oxygenated.

CONCLUSIONS

In view of the above discussions it may be concluded that the foraminiferal assemblage recovered from Keera hill, Kachchh represents a shallow water open marine environment confined within mid to outer shelf region, with normal salinity and high dissolved oxygen levels. However, minor fluctuations in the depositional environment have been detected on the basis of variations in various attributes of the foraminiferal assemblage (Figure 9).

The deposition of the sediments belonging to Chari Formation commenced in the outer shelf region with normal salinity and oxygen level (Palaeoecological Unit I). This was followed by shallowing of the depositional site to mid shelf region with normal salinity conditions and high oxygen level (Palaeoecological Unit II). Then the depositional site witnessed a transgressive phase with the basin attaining maximum depth in the outer shelf region, having normal salinity and oxygen enriched environment (Palaeoecological Unit III). A regression then followed with the depositional site once again shallowing to mid shelf region, having slightly greater water depth than in unit II, the salinity being normal and oxygen level high (Palaeoecological Unit IV). Again, there was a transgressive phase with the depositional site reaching to the outer shelf region, the water depth being slightly less than unit III, having normal salinity and high oxygen level (Palaeoecological Unit V).

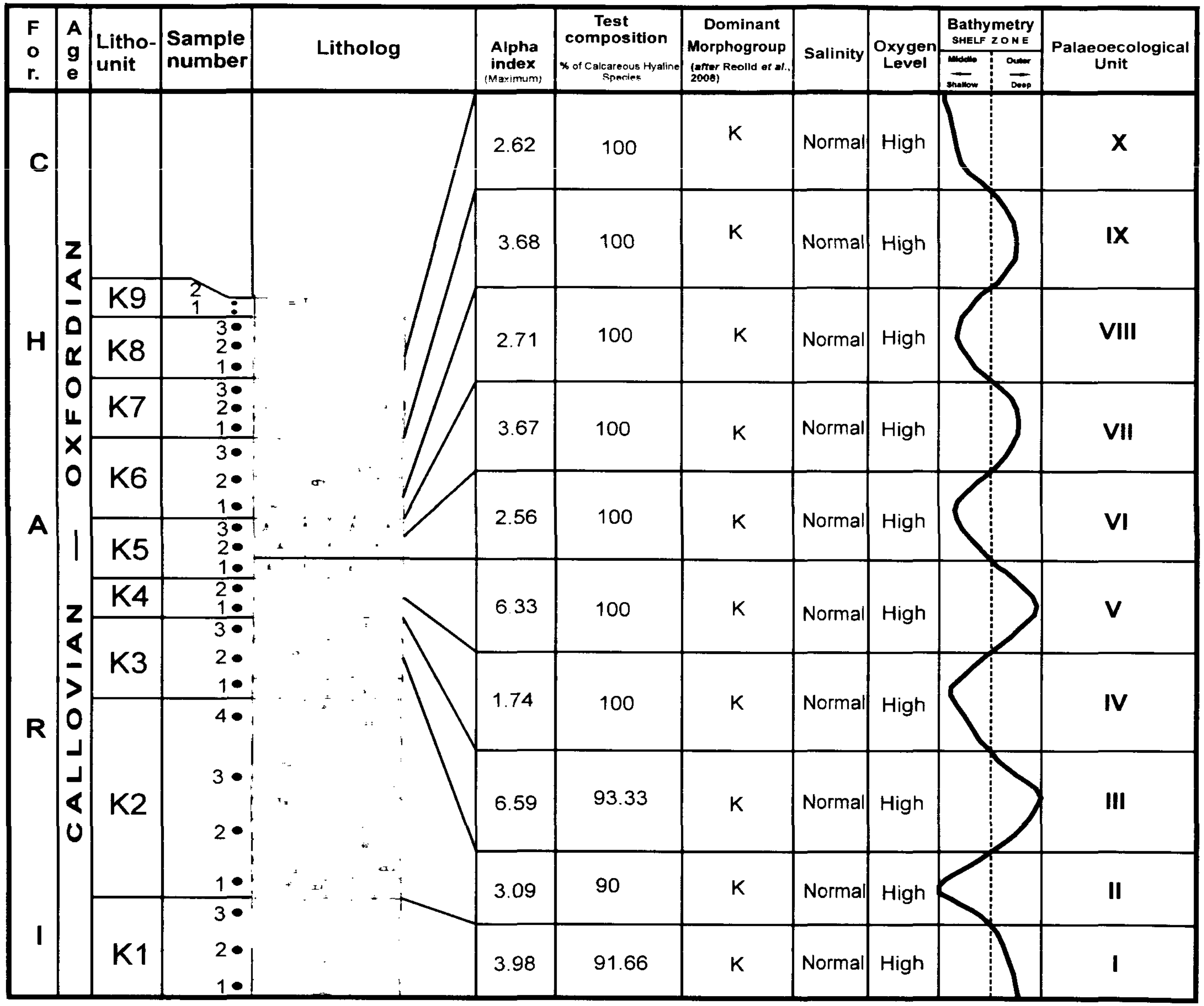


Figure 9. Main faunal parameters and inferred depositional environment of Callovian-Oxfrodian sequence, Keera hill, Kachchh

This was followed by another transgressive phase with the depositional site reaching into the shallower parts of the mid shelf region, but considerably deeper than in units II and IV, having normal salinity and high level of dissolved oxygen (Palaeoecological Unit VI). Another minor transgressive phase was then detected with the depositional site reaching to outer shelf region with the water depth being considerably shallower than units III and V but about equal to unit I, having normal salinity and well oxygenated water (Palaeoecological Unit VII). This was followed by a minor regressive phase in the mid shelf region with the water depth about equal to unit VI, where salinity was normal and oxygen level high (Palaeoecological Unit VIII). The depositional basin, once again, deepened slightly reaching the outer shelf and the water depth being about equal to unit VII, with normal salinity and rich oxygen level (Palaeoecological Unit IX). The final phase of deposition of the Chari sequence in the Keera area took place in the mid shelf region with constant shallowing of the basin where salinity was normal and water was well oxygenated ((Palaeoecological Unit X).

Although the deposition of the present sequence occurred in an open shallow marine environment confined to mid and outer shelf regions with normal salinity and high levels of dissolved oxygen, a number of minor transgressive and regressive events were detected as indicated by the frequent fluctuations in the water depth and migration of the strandline. This suggests that depositional basin was rather tectonically unstable with frequently fluctuating shoreline. However, the salinity was normal and the dissolved oxygen level remained high throughout the deposition of the studied sequence at Keera hill, Kachchh.

CHAPTER 6

SANDSTONE TEXTURE

INTRODUCTION

Texture of sandstone comprises grain size, roundness, sphericity, surface features, fabric, etc., mainly controlled by the hydrodynamic conditions prevailing at the time of deposition. Textural parameters are primarily related to nature of detritus shed from the provenance, mode and energy imparted during transportation. Variations in the texture of the sediments in relation to their environments have been studied by various workers (Folk, 1954; Folk and Ward, 1957; Mason and Folk, 1958; Friedman, 1961, 1962).

The study of grain size characteristic of sediments and their genetic interpretation have proved to be an interesting and challenging task over the years. Such studies require the help of statistical parameters in the interpretation of depositional environment and hydrodynamic condition obtaining at the time of deposition (Duane, 1964; McLaren, 1981; Sahu, 1983).

The grain size parameters and their relation with depositional processes have been published by Folk (1966), Moiola and Weiser (1968), Visher (1969), Friedman (1979). Beside these workers, Hoey and Ferguson (1994), Robinson and Slingerland (1998), Livingstone *et al.* (1999) also described the grain size distribution in relation to sedimentation dynamics.

Roundness of grain measures degree of sharpness of edges and corners and is a function of grain composition, size, type and distance of transport. Hard and resistant grains become rounded less readily during transport as compared to weakly durable grains. Larger grains are better rounded than the smaller ones for the same distance of transport. Various studies have established that roundness increases with distance of travel, rapidly in the beginning and slowly later on.

The degree of roundness also increases with the duration of transportation or reworking as shown by beach and desert sands which are, typically, more rounded than river or glacial outwash sand.

Wadell (1932) was the first to give measure of roundness of particle by dividing the average of the radii of the corners of the grain image by the radius of the maximum inscribed circle. Russell and Taylor (1937) placed particles in five classes of roundness based on comparison with photographs of type grains. Their class limits were not systematically chosen and arithmetic means of the intervals were used as mid-points. These values do not provide the smaller subdivisions that are needed in the lower values. Krumbein (1941) method is based on visual comparison of the individual grains, presented by nine different roundness values. Pettijohn (1948) and Power (1953) modified the roundness scale by using a geometric scale and presented five and six roundness classes, respectively.

Sphericity is a quantitative parameter measuring the departure of a body from equidimensionality. The sphericity of grain influences hydrodynamical behaviour of particle, affecting its settling velocity and mode of transport in a fluid current and, also, selective transportation. Krumbein (1940) observed that the sphericity of grains had a very significant effect on their settling velocity viz. the more nonspherical the particle, the lower the settling velocity. Transportability of grains in suspension, are also effected by sphericity, i.e., nonspherical grains tend to stay in suspension longer than the spherical ones. The relief of an area as well as intensity and type of weathering too play important role. Wadell (1932) defined sphericity as the ratio of the diameter of sphere with the same volume as a particle to the diameter of the smallest circle that would just enclose or circumscribe the outline of the particle.

METHOD OF STUDY AND DATA PRESENTATION

For textural analysis, fifty-one samples of Sandstone from Katrol Formation in Keera hill were taken from three different locations. The samples, being hard enough, were studied in thin sections. Grain size analysis was carried out by measuring the long axis of about 200-300 grains from each thin section with the help of ocular micrometer and point counting mechanical stage, as described by Chayes (1949).

The present study employed phi-scale of Krumbein (1934), which is much more convenient and simplified for analysis of grain size data. This size data were classed into half phi class intervals. The statistical parameters of grain size distribution were obtained with the help of cumulative frequency curves plots. The phi units at ϕ_5, ϕ_{16}, ϕ_{25}, ϕ_{50}, ϕ_{75}, ϕ_{84}, and ϕ_{95} percentiles were accurately read from the cumulative frequency curves. For the sandstones samples under study, the statistical parameters of grain size were calculated with the help of the formulae given by Folk (1968, 1980). The calculated parameters including Graphic mean size (M_z), Inclusive graphic standard deviation (σ_I), Inclusive graphic skewness (SK_I) and Graphic kurtosis (K_G). Roundness and sphericity were also analysed with the help of thin section and comparator charts.

STATISTICAL PARAMETERS

The statistical parameters of grain size based on the formulae of Folk (1980), like, Graphic mean (M_z), Inclusive graphic standard deviation (σ_I), Inclusive graphic skewness (SK_I) and Graphic kurtosis (K_G), were determined for the Sandstone samples of Katrol Formation.

Graphic mean size is a central tendency which indicates average size of the sediments. This is influenced by the source of supply, transporting medium, environment and the average kinetic energy of the depositional setting (Sahu, 1964).

Inclusive graphic standard deviation measure the average dispersion of distribution around mean or some other measure of central tendency. It indicate the difference in energy associated with the two modes of deposition.

Inclusive graphic skewness measures the degree of asymmetry of the frequency distribution, whereas, Graphic kurtosis measure peakedness of the frequency curve. Skewness and kurtosis have been referred to as indicators of selective action of transporting agent (Krumbein and Pettijohn, 1938). Since then these parameters have been employed by various investigators for interpreting depositional processes and environments. According to Folk and Ward (1957), sand deposited near the source are characteristically leptokurtic and positive skewed. Mason and Folk (1958) from their comparative textural studies of recent sands of beach, dune and aeolian flat environments found that beach sands were normal or negative skewed and leptokurtic, the dune sands had positive skewness and were mesokurtic, and the 'aeolian flat' sands were positively skewed and leptokurtic. Friedman (1961) observed that the beach sands generally, showed negative skewness, whereas, both dune and river sands usually showed positive skewness.

Location-I

The Graphic mean size (M_z) of the sandstone samples of Location-I ranges between 1.61ϕ to 3.25ϕ, 47% samples are fine-grained range, 35% are medium-grained and 18% are very fine-grained range (Table 3). Thus, the sandstones of the Location-I are mainly fine and medium-grained. The Inclusive graphic standard deviation (σ_I) or sorting values of the samples ranges between 0.53ϕ to 0.86ϕ. In the studied samples, about 59% are moderately sorted and 41% are moderately well-sorted (Table 3). Thus the sandstones are mainly moderately sorted and moderately well sorted.

The Inclusive graphic skewness (SK_I) values of sandstone samples range between –0.08 to 0.13, 65% sandstone samples are near symmetrical and 35% are fine-skewed (Table 3). Thus, the Location-I sandstones are mostly near symmetrical and fine-skewed. The Graphic kurtosis (K_G) value of the samples of Location-I range between 0.91 to 1.29 (Table 3). About 24% sandstone are leptokurtic but, most of the samples are mesokurtic (76%) (Table 3).

Location-II

The sandstone samples of Location-II show values of Graphic mean size (M_z) between 1.56ϕ to 2.31ϕ. Of the total samples about 56% samples are fine-grained and 44% are medium grained (Table 3). Thus, the samples are only fine and medium grained. Their Inclusive graphic standard deviation (σ_I) values range between 0.69ϕ to 0.96ϕ. About 78% samples are moderately sorted and 22% are moderately well sorted (Table 3). Thus, the Location-II sandstones are mainly moderately sorted. The Skewness (SK_I) values of the Location-II sandstone ranges between -0.25 to 0.03 (Table 3). The skewness of 55% samples are near symmetrical and 45% are coarse skewed. Thus, the sandstones are near symmetrical and coarse skewed. The Kurtosis (K_G) values of the samples ranges between 0.87 to 1.13. About 61% samples are mesokurtic followed by 22% platykurtic and 17% leptokurtic (Table 3). Thus, the sandstones of Location-II are mainly mesokurtic, some are platykurtic and leptokutic.

Location-III

Graphic mean size (M_z) of the Location-III sandstones range between 1.63ϕ to 3.45ϕ. The mean size of about 44% samples lies under fine-grained, 37% are medium-grained and 19% are very fine-grained (Table 3). Thus, the sandstones are mainly fine and medium-grained, only few are very fine-grained.

The Inclusive graphic standard deviation (σ_I) or sorting values of sandstone ranges between 0.53ϕ to 1.30ϕ. About 56% samples are moderately sorted followed by 38% moderately well sorted and 6% poorly sorted (Table 3).

Table 3: Statistical parameters of grain size distribution of Katrol Formation (Upper Jurassic), Keera Hill Sandstone based on Folk's (1968) method

M_Z= Graphic mean, σ_1 inclusive graphic standard deviation (sorting), SK_I = Inclusive graphic skewness
K_G= Graphic Kurtosis

Sample No.	MZ	Verbal Limit	σ_1	Verbal Limit	SK_I	Verbal Limit	KG	Verbal Limit
Location-I								
KM-1	2.71	Fine	0.54	Moderately well sorted	0.10	Fine skewed	1.29	Leptokurtic
KM-2	2.28	Fine	0.73	Moderately sorted	-0.08	Near symmetrical	1.27	Leptokurtic
KM-4	3.11	Very Fine	0.53	Moderately well sorted	0.11	Fine skewed	0.92	Mesokurtic
KM-7	2.91	Fine	0.71	Moderately sorted	0.05	Near symmetrical	1.15	Leptokurtic
KM-10	2.83	Fine	0.65	Moderately well sorted	0.04	Near symmetrical	1.03	Mesokurtic
KM-12	1.81	Medium	0.82	Moderately sorted	0.01	Near symmetrical	0.93	Mesokurtic
KM-15	1.61	Medium	0.86	Moderately sorted	0.03	Near symmetrical	0.91	Mesokurtic
KM-17	1.85	Medium	0.74	Moderately sorted	0.01	Near symmetrical	0.91	Mesokurtic
KM-19	1.98	Medium	0.86	Moderately sorted	-0.01	Near symmetrical	1.02	Mesokurtic
KM-20	2.16	Fine	0.75	Moderately sorted	0.13	Fine skewed	0.95	Mesokurtic
KM-22	3.01	Very Fine	0.58	Moderately well sorted	0.13	Fine skewed	0.97	Mesokurtic
KM-25	2.11	Fine	0.69	Moderately well sorted	-0.01	Near symmetrical	0.99	Mesokurtic
KM-29	2.28	Fine	0.72	Moderately sorted	0.13	Fine skewed	1.07	Mesokurtic
KM-31	3.25	Very Fine	0.54	Moderately well sorted	0.08	Near symmetrical	0.98	Mesokurtic
KM-35	2.40	Fine	0.66	Moderately well sorted	-0.06	Near symmetrical	1.17	Leptokurtic
KM-39	1.95	Medium	0.86	Moderately sorted	-0.07	Near symmetrical	0.91	Mesokurtic
KM-40	1.95	Medium	0.75	Moderately sorted	0.13	Fine skewed	0.93	Mesokurtic
Location-II								
KS-2	1.91	Medium	0.93	Moderately sorted	-0.01	Near symmetrical	0.87	Platykurtic
KS-4	1.96	Medium	0.88	Moderately sorted	-0.23	Coarse skewed	0.88	Platykurtic
KS-5	2.10	Fine	0.84	Moderately sorted	-0.12	Coarse skewed	1.01	Mesokurtic
KS-9	2.25	Fine	0.59	Moderately well sorted	0.03	Near symmetrical	0.94	Mesokurtic
KS-10	1.56	Medium	0.96	Moderately sorted	-0.07	Near symmetrical	0.94	Mesokurtic
KS-13	2.16	Fine	0.70	Moderately well sorted	-0.14	Coarse skewed	0.87	Platykurtic
KS-14	2.13	Fine	0.71	Moderately sorted	-0.05	Near symmetrical	1.13	Leptokurtic
KS-22	2.30	Fine	0.83	Moderately sorted	-0.12	Coarse skewed	1.04	Mesokurtic
KS-25	2.15	Fine	0.76	Moderately sorted	-0.08	Near symmetrical	0.97	Mesokurtic
KS-26	2.21	Fine	0.82	Moderately sorted	-0.13	Coarse skewed	0.83	Platykurtic

KS-30	1.98	Medium	0.75	Moderately sorted	0.12	Coarse skewed	1.13	Leptokurtic
KS-31	1.91	Medium	0.94	Moderately sorted	-0.25	Coarse skewed	0.97	Mesokurtic
KS-33	2.05	Fine	0.89	Moderately sorted	-0.05	Near symmetrical	0.98	Mesokurtic
KS-34	1.55	Medium	0.79	Moderately sorted	-0.01	Near symmetrical	1.01	Mesokurtic
KS-35	1.73	Medium	0.70	Moderately well sorted	0.08	Near symmetrical	0.91	Mesokurtic
KS-36	2.31	Fine	0.75	Moderately sorted	-0.10	Near symmetrical	1.12	Leptokurtic
KS-38	2.25	Fine	0.69	Moderately well sorted	-0.08	Near symmetrical	0.96	Mesokurtic
KS-40	1.91	Medium	0.88	Moderately sorted	-0.17	Coarse skewed	1.03	Mesokurtic
Location-III								
KB-2	2.61	Fine	0.73	Moderately sorted	-0.03	Near symmetrical	1.03	Mesokurtic
KB-4	1.93	Medium	0.74	Moderately sorted	-0.06	Near symmetrical	0.87	Platykurtic
KB-5	2.16	Fine	0.83	Moderately sorted	-0.03	Near symmetrical	1.11	Leptokurtic
KB-7	2.76	Fine	0.53	Moderately well sorted	0.07	Near symmetrical	1.22	Leptokurtic
KB-8	2.25	Fine	0.79	Moderately sorted	-0.30	Coarse skewed	1.25	Leptokurtic
KB-9	1.80	Medium	0.87	Moderately sorted	-0.22	Coarse skewed	1.02	Mesokurtic
KB-14	1.63	Medium	0.95	Moderately sorted	-0.09	Near symmetrical	0.99	Mesokurtic
KB-17	1.85	Medium	0.82	Moderately sorted	-0.10	Near symmetrical	0.98	Mesokurtic
KB-20	3.06	Very Fine	0.60	Moderately well sorted	0.13	Fine skewed	1.02	Mesokurtic
KB-23	1.68	Medium	1.30	Poorly sorted	-0.35	Strongly coarse skewed	1.03	Mesokurtic
KB-24	2.76	Fine	0.59	Moderately well sorted	0.03	Near symmetrical	1.12	Leptokurtic
KB-25	3.03	Very Fine	0.54	Moderately well sorted	0.17	Fine skewed	1.03	Mesokurtic
KB-28	2.65	Fine	0.53	Moderately well sorted	0.07	Near symmetrical	1.19	Leptokurtic
KB-32	1.98	Medium	0.73	Moderately sorted	-0.18	Coarse skewed	0.96	Mesokurtic
KB-34	2.43	Fine	0.90	Moderately sorted	0.06	Near symmetrical	0.93	Mesokurtic
KB-38	3.45	Very Fine	0.54	Moderately well sorted	-0.04	Near symmetrical	1.01	Mesokurtic

Thus, the Location-III sandstones are mainly moderately sorted and moderately well sorted, only one sample is poorly sorted. The Skewness (SK_I) values of the sandstones range between -0.35 to 0.17. About 63% samples near symmetrical, 19% coarse skewed, 13% fine skewed and 6% strongly coarse skewed (Table 3). Thus, the sandstone of Location-III is mainly near symmetrical. The Kurtosis (K_G) values ranges between 0.87 to 1.25. The samples are mostly mesokurtic (63%), followed by leptokurtic (31%) and platykurtic (6%) (Table 3). Thus, the sandstones are mainly mesokurtic and leptokutic.

The area level study indicate that the graphic mean (M_z) values ranges between 1.55ϕ to 3.45ϕ. Out of the total samples, 49% are fine-grained, 39% medium-grained and 12% very fine- grained (Table 3). Thus, the sandstones are mainly fine and medium-grained. The Inclusive graphic standard deviation (σ_I) or sorting values of sandstone ranges between 0.53ϕ to 1.30ϕ. About 65% samples are moderately sorted, 33% are moderately well sorted and 2% are poorly sorted (Table 3). Thus, the sandstones are mainly moderately sorted and moderately well sorted. The Inclusive graphic skewness (SK_I) value of the sandstone ranges between -0.35 to +17. About 61% sandstones are near symmetrical followed by 22% coarse skewed, 15% fine skewed and 2% strongly coarse skewed (Table 3). Thus, the sandstones are mainly near symmetrical. The Graphic kurtosis (K_G) value of sandstone samples range between 0.83 to 1.25. Of the total number of samples, about 67% are mesokurtic, 23% leptokurtic and 10% platykurtic (Table 3). Thus, the sandstones are mainly mesokurtic.

ROUNDNESS

The Roundness of grains was determined by taking 100 to 200 grains from each thin section using visual comparison charts and verbal roundness scale of Power (1953). The interval between roundness classes is approximately equal to $\sqrt{2}$, i.e. the interval of each class is 1.41 times greater than the preceding class. The percentage of each roundness classes and mean roundness of various samples are given in Table 4.

Location-I

The mean roundness values range between 0.34 to 0.41. Subrounded grains dominate (44.91%) followed by subangular (35.17), rounded (10.81%), angular (6.14%) well-rounded (2.36%) and very-angular ones (1.24%) (Table 4). Thus, most of the grains are subangular to subrounded and mean roundness is 0.38.

Location-II

The mean roundness value of individual samples ranges between 0.33 to 0.40. The grain roundness averages 1.06% very angular, 7.10% angular, 37.11% subangular, 43.52% subrounded, 9.50% rounded and 1.71% well rounded (Table 4). Majority of grains are subangular to subrounded and mean roundness is 0.37.

Location-III

Mean roundness value ranging between 0.34 to 0.40. The average of about 0.90% grains are very-angular, 6.34% are angular, 38.59% are subangular, 43.58% are subrounded, 8.73% are rounded and 1.86% are well rounded (Table 4). The dominant roundness class is subangular to subrounded. The mean roundness value for aggregate distribution is 0.37.

Table 4: **Roundness of detrital grains of Katrol Formation (Upper Jurassic), Keera Hill Sandstone, Kachchh, (Roundness classes) based on Power's (1953) scale**
N= Number of grains, % percentage

Sample No.	Total number of grains	Very Angular (0.12-0.17)		Angular (0.17-0.25)		Sub-Angular (0.25-0.35)		Sub-Rounded (0.35-0.49)		Rounded (0.49-0.70)		Well Rounded (0.70-1.0)		Mean Rounded
		N	%	N	%	N	%	N	%	N	%	N	%	
Location-I														
KM-1	126	—	—	—	—	42	33.33	65	51.59	14	11.11	5	3.97	0.41
KM-2	122	—	—	2	1.64	43	35.24	62	50.82	14	11.48	1	0.82	0.39
KM-4	140	—	—	2	1.43	39	27.86	78	55.71	17	12.14	4	2.86	0.41
KM-7	110	4	3.64	12	10.90	52	47.27	35	31.82	6	5.46	1	0.91	0.34
KM-10	140	2	1.43	13	9.28	61	43.57	51	36.43	11	7.86	2	1.43	0.35
KM-12	112	2	1.78	9	8.04	35	31.25	52	46.43	11	9.82	3	2.68	0.38
KM-15	108	—	—	6	5.55	45	41.67	48	44.44	8	7.41	1	0.93	0.37
KM-17	124	2	1.61	12	9.68	44	35.48	56	45.16	10	8.07	—	—	0.36
KM-19	119	4	3.36	11	9.24	48	40.34	47	39.50	9	7.56	—	—	0.35
KM-20	114	2	1.75	11	9.65	38	33.33	52	45.62	9	7.90	2	1.75	0.37
KM-22	130			7	5.38	40	30.77	63	48.46	16	12.31	4	3.08	0.40
KM-25	113	4	3.54	9	7.96	32	28.32	49	43.36	13	11.51	6	5.31	0.39
KM-29	131	—	—	9	6.87	51	38.93	55	41.98	14	10.69	2	1.53	0.37
KM-31	134	—	—	2	1.49	47	35.08	61	45.52	18	13.43	6	4.48	0.41
KM-35	126	—	—	5	3.97	40	31.74	60	47.62	16	12.70	5	3.97	0.40
KM-39	129	2	1.55	9	6.98	43	33.33	59	45.74	13	10.08	3	2.32	0.38
KM-40	125	3	2.40	8	6.40	38	30.40	54	43.20	17	13.60	5	4.00	0.39
Location-II														
KS-2	164	1	0.61	14	8.54	63	38.41	65	39.63	18	10.98	3	1.83	0.37
KS-4	102	2	1.96	7	6.86	32	31.37	48	47.06	9	8.83	4	3.92	0.38
KS-5	124	3	2.42	14	11.29	58	46.77	39	31.45	9	7.26	1	0.81	0.34
KS-9	141	4	2.84	12	8.51	74	52.48	43	30.50	7	4.96	1	0.71	0.33
KS-10	102	—	—	7	6.86	37	36.28	45	44.12	11	10.78	2	1.96	0.38
KS-13	153	1	0.65	12	7.84	60	39.22	66	43.14	12	7.84	2	1.31	0.36
KS-14	117	—	—	7	5.98	43	36.75	58	49.58	9	7.6	—	—	0.37
KS-22	120	1	0.84	6	5.00	40	33.33	60	50.00	10	8.33	3	2.50	0.38
KS-25	105	—	—	5	4.76	32	30.48	54	51.43	13	12.38	1	0.95	0.39

KS-26	118	—	—	4	3.39	42	35.59	58	49.15	12	10.17	2	1.70	0.38
KS-30	132	—	—	11	8.34	45	34.09	57	43.18	16	12.12	3	2.27	0.38
KS-31	113	2	1.77	7	6.19	34	30.09	53	46.90	12	10.62	5	4.43	0.39
KS-33	124	4	3.23	10	8.06	42	33.87	47	37.90	18	14.52	3	2.42	0.38
KS-34	115	—	—	9	7.83	31	26.96	58	50.43	13	11.30	4	3.48	0.40
KS-35	107	—	—	6	5.61	35	32.71	54	50.47	12	11.21	—	—	0.38
KS-36	162	3	1.85	14	8.64	77	47.53	56	34.57	12	7.41	—	—	0.34
KS-38	174	2	1.15	12	6.90	78	44.83	70	40.23	11	6.32	1	0.57	0.35
KS-40	110	2	1.82	8	7.27	41	37.27	48	43.64	9	8.18	2	1.82	0.37
Location-III														
KB-2	110	2	1.82	8	7.27	31	28.18	51	46.36	12	10.91	6	5.46	0.40
KB-4	112	—	—	9	8.03	41	36.61	51	45.54	11	9.82	—	—	0.37
KB-5	104	2	1.92	13	12.50	41	39.42	39	37.50	9	8.66	—	—	0.35
KB-7	149	—	—	12	8.05	67	44.97	56	37.58	14	9.40	—	—	0.36
KB-8	112	1	0.89	5	4.46	34	30.36	60	53.57	9	8.04	3	2.68	0.39
KB-9	123	3	2.45	11	8.94	51	41.46	49	39.84	8	6.50	1	0.81	0.35
KB-14	111	1	0.90	5	4.50	42	37.84	52	46.85	7	6.31	4	3.60	0.38
KB-17	130	2	1.54	12	9.23	44	33.84	53	40.77	15	11.54	4	3.08	0.37
KB-20	140	2	1.43	9	6.43	72	51.43	52	37.14	5	3.57	—	—	0.34
KB-23	115	—	—	8	6.96	48	41.73	50	43.48	9	7.83	—	—	0.36
KB-24	194	—	—	8	4.12	76	39.18	87	44.85	19	9.79	4	2.06	0.38
KB-25	169	—	—	5	2.96	73	43.20	78	46.16	12	7.10	1	0.59	0.37
KB-28	167	—	—	4	2.40	65	38.92	77	46.11	15	8.98	6	3.59	0.39
KB-32	122	1	0.82	5	4.10	41	33.61	55	45.08	16	13.11	4	3.28	0.40
KB-34	132	2	1.52	9	6.82	50	37.88	57	43.18	11	8.33	3	2.27	0.37
KB-38	173	2	1.16	8	4.62	67	38.73	75	43.35	17	9.83	4	2.31	0.38

On the area level, mean roundness value of individual samples ranges between 0.33 to 0.41. The grain roundness averages 1.06% very-angular, 6.53% angular, 36.96% subangular, 44.00% subrounded, 9.47% rounded and 1.98% well rounded (Table 4). Thus, most of grains are subangular to subrounded. The grain roundness distribution of studied sandstone shows unimodal distribution with subrounded class modal class. The mean roundness for aggregate distribution is 0.37.

SPHERICITY

The sphericity values of detrital grains of the sandstones of Katrol Formation, gave High and Low sphericity, according to visual comparative chart given by Power (1953).

Location-I

The mean grain sphericity value for sandstones of this location range between 0.41 to 0.56. The average mean sphericity for the aggregate samples is 0.48. On an average, about 34.39% grains show high sphericity and 65.61% show low sphericity (Table 5).

Location-II

The mean sphericity values range between 0.41 to 0.55 and the average 0.48. About 33.78% grains show high sphericity and 66.22% show low sphericity is represented (Table 5).

Location-III

The mean sphericity value range between 0.45 to 0.58 and average as 0.51. About 37.72% grains show high sphericity and 62.28% low sphericity (Table 5).

Table 5: Sphericity of detrital grains of Katrol Formation (Upper Jurassic), Keera hill Sandstone, Kachchh

Sample No.	Total number of grains	High Sphericity (>0.9)		Low Sphericity (<0.3)		Mean Sphricity
		Number of Grains	Percentage	Number of Grains	Percentage	
Location-I						
KM-1	172	45	26.16	127	73.84	0.43
KM-2	135	43	31.85	92	68.15	0.47
KM-4	158	60	37.97	98	62.03	0.51
KM-7	129	30	23.26	99	76.74	0.41
KM-10	188	63	33.51	125	66.49	0.48
KM-12	134	41	30.60	93	69.40	0.46
KM-15	110	32	29.09	78	70.91	0.45
KM-17	158	66	41.77	92	58.23	0.54
KM-19	143	55	38.46	88	61.54	0.51
KM-20	142	58	40.85	84	59.15	0.53
KM-22	158	70	44.30	88	55.70	0.53
KM-25	151	45	29.80	106	70.20	0.45
KM-29	141	43	30.50	98	69.50	0.46
KM-31	149	54	36.24	95	63.76	0.50
KM-35	144	54	37.50	90	62.50	0.51
KM-39	161	56	34.78	105	65.22	0.49
KM-40	134	51	38.06	83	61.94	0.51
Location-II						
KS-2	137	56	40.88	81	59.12	0.53
KS-4	140	41	29.29	99	70.71	0.45
KS-5	118	37	31.36	81	68.64	0.46
KS-9	117	45	38.46	72	61.54	0.51
KS-10	125	46	36.80	79	63.20	0.50
KS-13	131	46	35.11	85	64.89	0.49
KS-14	124	30	24.19	94	75.81	0.41
KS-22	134	39	29.10	95	70.90	0.45
KS-25	141	49	34.75	92	65.25	0.49
KS-26	184	58	31.52	126	68.48	0.47
KS-30	134	37	27.61	97	72.39	0.44
KS-31	141	50	35.46	91	64.54	0.49

KS-33	148	38	25.68	110	74.32	0.42
KS-34	149	53	35.57	96	64.43	0.49
KS-35	133	40	30.08	93	69.92	0.46
KS-36	163	70	42.94	93	57.06	0.55
KS-38	184	72	39.13	112	60.87	0.52
KS-40	122	49	40.16	73	59.84	0.53
Location-III						
KB-2	144	50	34.72	94	65.28	0.49
KB-4	128	37	28.91	91	71.09	0.45
KB-5	118	38	32.20	80	67.80	0.47
KB-7	130	52	40.00	78	60.00	0.53
KB-8	102	47	46.08	55	53.92	0.57
KB-9	142	48	33.80	94	66.20	0.48
KB-14	128	42	32.81	86	67.19	0.47
KB-17	145	54	37.24	91	62.76	0.51
KB-20	128	46	35.94	82	64.06	0.50
KB-23	103	39	37.86	64	62.14	0.51
KB-24	156	74	47.44	82	52.56	0.58
KB-25	166	56	33.73	110	66.27	0.48
KB-28	132	42	31.82	90	68.18	0.47
KB-32	150	58	38.67	92	61.33	0.52
KB-34	154	70	45.45	84	54.55	0.56
KB-38	171	80	46.78	91	53.22	0.57

On the area level, mean sphericity values ranges from 0.40 to 0.41. The average mean sphericity for aggregate distribution 0.49. On an average, about 35.30% grains show high sphericity and 64.70% low sphericity (Table 5).

CHAPTER 7

DETRITAL MINERALOGY, PETROFACIES AND TECTONIC SETTING

INTRODUCTION

The detrital modes of sandstone primarily reflect the tectonic setting of the provenance. It is also influenced by the character of sedimentary provenance, the nature of the sedimentary processes within the depositional basin, and the kind of dispersal paths that link the provenance to basin. The relationship between provenance and basin is governed by plate-tectonics which, thus, ultimately controls the distribution and type of sandstone (Schwab, 1975; Folk, 1980; Valloni and Maynard, 1981). During the last two decades several authors (Graham *et al.*, 1976, 1993; Dickinson and Suczek, 1979; Ingersoll and Suczek, 1979; Dickinson and Valloni, 1980; Zuffa, 1980; Ingersoll *et al.*, 1984; Valloni and Mezzadri, 1984; Dickinson, 1985; Ingersoll, 1990) have demonstrated a close correlation between composition of sandstones and plate-tectonic setting.

The composition of sandstone and its relation to tectonic setting was first envisioned by Krynine (1942) in terms of prevalent concept of geosynclinal cycle. Detrital modes of sandstones, interpreted in relation to plate-tectonic setting, have led to the recognition and description of 'Petrofacies' in the sedimentary sequence. The petrofacies are those facies which can be distinguished by their distinct composition and appearances. This has extensively been used in the studies pertaining to sandstone petrography and were found useful in diagnosing the tectonic heritance and provenance evolution (Gilbert and Dickinson, 1970; Dickinson and Rich, 1972; Dickinson and Suczek, 1979). Various studies on petrofacies of sandstone suites and their collation and comparison to their provenance with tectonic setting has been established with the help of modal ternary diagrams. Dickinson and Suczek (1979) were first to give ternary diagram using quartz, feldspar and lithic fragments.

The interpretation of tectono-provenance with the help of these ternary diagrams holds good for most of the sandstone suits and has been widely used to understand the tectonic evolution of a provenance-basin and also for study of long term evolution of geoprovince and its sedimentary cover (Dickinson *et al.*, 1983; Schwab, 1991; Skillbeck and Cawood, 1994; Qayyum *et al.*, 2001).

Various recent studies of sandstone petrofacies of different ages undertaken on a regional scale were used to interpret their tectonic evolution (Schwab, 1991; Graham *et al.*, 1993; Cox and Lowe, 1995; Critell *et al.*, 1995; Trop and Ridgway, 1997). The evolutionary trends in sandstone composition within individual basins or sedimentary provinces commonly reflect change in tectonic setting through time or erosional modification of provenance terranes (Dickinson, 1985).

Although detrital modes of sandstone suits primarily reflect the tectonic setting of provenance terrains, various other sedimentological factors also influence the sandstone composition, though, sometimes strongly. Other secondary factors like relief, climate, transport mechanism, depositional environment and digenetic changes can also be important in determining the detrital composition of sandstone (Pettijohn *et al.*, 1972; Suttner, 1974).

The present study of the detrital mineralogy of the sandstones of Katrol Formation (Keera Hill) have been attempted for petrographic classification and the interpretation of their provenance and plate-tectonic setting.

METHOD OF STUDY

The detrital mineral composition of sandstone was evaluated both qualitatively and quantitatively. The study is based on sixty-one sandstone samples of Katrol Formation, Keera Hill, from three different locations. The samples were selected equispaced both vertically and laterally. For quantitative analysis, for determining the modal composition, about 300-400 point grains were counted from each rock thin section according to the 'Gazzi-Dickinson method' (Zuffa, 1980; Ingersoll *et al.* 1984). A grid spacing larger than the maximum framework grain size was used. An attempt was also made to recognize those mineral grains and/or lithic fragments that were extensively diagenetically altered (McBride, 1985). To distinguish K-feldspar from plagioclase-feldspar, the thin sections were stained with sodium-cobaltinitrite solution (Bailey and Stevens, 1960).

The terminology proposed by Folk (1980) was employed for identifying and describing the detrital grains of the sandstones. Various petrofacies identified were recalculated to 100 percent following the methods developed by Ingersoll and Suczek (1979) and Dickinson (1985). These petrofacies were plotted on the standard triangular diagram QtFL, QmFLt, QmPK (Dickinson, 1985) and QpLvmLsm, LmLvLs (Ingersoll and Suczek, 1979; Suczek and Ingersoll, 1985).

DETRITAL MINERALOGY

The framework constituents of the sandstone mainly consists of several varieties of quartz, followed by feldspar, mica, chert, lithic fragments and heavy minerals. The average percentage of different detrital constituent of sandstones are: quartz 78.92%, feldspar 14.13%, mica 3.20%, chert 1.19%, lithic fragments 1.09% and heavy minerals 1.47%, (Table 6).

Quartz

Quartz is the dominant mineral constituent in the sandstones. On the basis of grain shape boundaries, extinction and inclusion pattern, different varieties of quartz recognized and described as proposed by Folk (1980).

Common Quartz

Common quartz is monocrystalline with straight to slightly undulose extinction. The grains occur as sub-equant, and mostly subangular to subrounded. Most of the grains present are show clear appearance, only a few of them show inclusion of mica, tourmaline, rutile, zircon and opaques.

Vein Quartz

Vein quartz occurs in very small percentage are mono- crystalline with abundant vacuoles and cloudy appearance. They also show semi-composite to straight or undulose extinction. The grains are mostly subangular to subrounded.

Recrystallized Metamorphic Quartz

The recrystallized metamorphic quartz occurs as polycrystalline grains of equant to subequant shape and are subrounded to rounded. The grains are made up of a mosaic of microcrystalline to fine grained sub-individuals. The sub-individuals are equidimensional with straight to curvi-planar boundaries with widely different optical orientations. In a few thin sections, the sub-individuals grains are polygonal in shape.

Streached Metamorphic Quartz

Streached metamorphic quartz comprise subrounded to rounded polycrystalline grains with elongated and lensoid sub-individuals. The later shows almost subparallel to parallel orientation, with smooth, more or less straight, sometime sutured and curved boundaries. The sub-individuals show highly undulose extinction.

Feldspar

Feldspars are the second most abundant mineral in these sandstones. The grains are generally sub-equant, with subangular to subrounded outline. K-feldspar were identified by sodium-cobaltinitrite stain test. Some of the stained grains with cross-hatched twinning are recognized as microcline, and those without such twinning as orthoclase. The unstained feldspars with characteristic lamellar twinning were identified as plagioclase. However, a few untwined plagioclase are also recognized showing perfect cleavages. Some perthite grains are also identified in a few thin sections on the basis of their characteristic intergorwth texture.

The feldspars are generally fresh, and of clear appearance, but a few grains show alteration along the cleavage. Minor inclusions are also present in feldspar. Some feldspars also show complete change into Kaolinite.

Mica

Both the varieties of mica, muscovite and biotite, have been recognised, which occur as tiny flakes to large elongated lath-shaped fragments with frayed ends. However, muscovite is more common than biotite. The later being generally green and brown in colour. The large laths of mica show bending and kinking around detrital grains as a result of compaction.

Chert

Chert occurs mostly as subrounded to rounded grains. In thin section, they appear as made of aggregate of microcrystalline quartz crystals with peculiar pinpoint birefringence. A few grains contain some impurity of ferruginous material, thereby; ferruginous and non-ferruginous type of chert can be distinguished.

Table 6: Percentage of detrital minerals in the Katrol Formation (Upper Jurassic), Keera Hill Sandstone, Kachchh

CQ=Common Quartz, VQ=Vein Quartz, RMQ=Recrystallized Metamorphic Quartz, SMQ=Streached Metamorphic Quartz, KF=Potassium Feldspar, PF=Plagioclass Feldspar, MLF=Metamorphic Lithic Fragments, SLF=Sedimentory Lithic Fragments, VLF=Volcanic Lithic Fragments

Sample No.	Monocrystalline Quartz (Qm)		Polycrystalline Quartz (Qpq)		Feldspar (F)		Mica (M)	Chert (C)	Lithic Fragments (L)			Heavy Minerals (H)
	CQ	VQ	RMQ	SMQ	KF	PF			MLF	SLF	VLF	
LOCATION-I												
KM-1	78.06	0.76	0.51	0.25	4.34	7.91	3.83	1.28	1.28	0.25	0.25	1.28
KM-2	76.12	0.37	1.12	1.12	7.83	5.60	4.10	1.49	0.76	0.37	-	1.12
KM-4	80.51	0.78	0.52	0.52	3.90	6.49	2.86	1.30	0.78	0.26	-	2.08
KM-7	74.03	0.43	0.87	0.43	5.20	10.39	6.06	1.73	0.43	0.43	-	-
KM-9	76.69	0.61	0.61	0.31	3.99	8.90	4.29	0.61	1.53	0.31	-	2.15
KM-10	73.45	1.08	0.54	0.81	5.96	8.13	4.61	2.71	1.36	0.27	-	1.08
KM-11	76.15	0.58	1.15	0.86	6.03	7.47	2.87	2.01	0.29	0.29	-	2.30
KM-12	74.64	1.07	0.71	1.79	4.29	11.78	1.07	1.07	0.36	0.36	-	2.86
KM-13	72.25	1.14	0.76	0.38	7.22	7.99	3.04	2.66	0.76	0.38	-	3.42
KM-15	75.36	1.45	2.17	3.62	5.07	6.52	1.45	1.45	0.73	0.73	-	1.45
KM-17	80.00	0.71	1.43	1.07	6.43	6.79	1.43	0.71	0.36	0.36	-	0.71
KM-19	76.07	0.71	1.79	0.71	4.64	9.65	2.86	1.43	0.71	0.36	-	1.07
KM-20	77.36	0.63	0.94	0.63	6.92	7.23	1.26	0.94	0.63	0.31	-	3.15
KM-21	80.07	-	0.65	0.33	2.94	6.86	3.59	1.31	0.33	0.65	0.33	2.94
KM-22	75.27	0.81	0.54	0.54	3.49	10.75	3.49	0.81	0.54	0.27	-	3.49
KM-25	72.44	2.36	1.58	1.18	5.91	11.02	2.76	0.39	0.79	0.39	-	1.18
KM-29	73.08	-	1.92	1.44	5.77	8.65	5.29	2.41	0.48	-	0.48	0.48
KM-31	74.32	0.68	0.34	0.34	8.11	8.44	4.05	0.68	0.68	-	-	2.36
KM-35	71.34	0.62	0.94	0.62	8.10	9.35	6.23	0.62	0.62	0.31	0.31	0.94
KM-39	77.55	1.63	2.04	1.23	4.90	5.71	2.45	2.04	-	0.41	-	2.04
KM-40	76.98	1.37	1.03	0.69	8.94	6.53	1.72	1.37	0.34	0.34	-	0.69
LOCATION-II												
KS-2	77.50	1.43	1.79	2.50	6.07	8.22	0.71	0.71	0.36	-	-	0.71
KS-4	71.43	2.31	0.92	0.92	10.60	6.91	3.69	0.92	0.46	0.46	-	1.38
KS-5	76.60	1.77	1.77	0.71	6.38	7.80	2.14	0.35	1.42	-	-	1.06
KS-7	72.85	0.99	0.99	1.99	8.61	7.29	3.64	1.99	-	0.33	-	1.32
KS-9	73.76	1.06	0.71	1.06	5.68	10.64	4.61	0.71	1.06	-	-	0.71

KS-10	73.62	3.07	2.46	1.23	7.36	5.52	3.68	0.61	0.61	0.61	-	1.23
KS-13	74.11	1.30	1.30	1.94	5.18	10.03	3.24	0.97	0.32	0.32	0.32	0.97
KS-14	74.90	1.54	1.16	0.77	8.88	7.34	2.70	1.16	0.39	-	-	1.16
KS-16	77.48	0.76	1.15	0.38	8.40	6.87	3.06	0.38	0.38	0.38	-	0.76
KS-20	74.24	1.31	0.44	0.87	7.42	6.55	7.42	0.87	-	0.44	-	0.44
KS-22	75.19	0.74	1.48	1.11	7.78	7.78	4.07	0.74	0.37	0.74	-	-
KS-25	73.20	0.80	1.60	1.20	8.80	9.20	2.40	0.80	0.40	-	-	1.60
KS-26	72.66	-	1.44	0.72	7.55	9.71	2.88	1.80	-	0.72	-	2.52
KS-29	75.91	1.65	0.66	0.99	7.59	8.91	1.65	0.66	0.33	0.33	-	1.32
KS-30	79.13	0.36	2.16	0.72	6.12	6.47	1.80	1.08	-	0.72	0.36	1.08
KS-31	73.73	0.46	3.23	2.31	5.07	6.91	5.07	0.92	0.46	0.46	0.46	0.92
KS-33	74.23	0.38	1.54	1.16	8.08	9.23	1.54	0.38	0.77	-	-	2.69
KS-34	76.27	0.68	1.69	2.37	7.46	5.76	3.05	0.34	0.34	0.68	-	1.36
KS-35	77.35	-	1.66	0.55	5.53	6.63	3.87	1.10	1.10	-	-	2.21
KS-36	80.06	-	1.53	0.92	5.83	8.28	2.15	0.61	0.31	0.31	-	-
KS-38	76.67	0.61	1.82	2.42	8.79	5.15	1.51	1.51	0.61	-	-	0.91
KS-40	77.78	1.45	2.90	2.42	2.90	7.25	1.93	0.48	0.48	0.48	-	1.93
LOCATION-III												
KB-2	71.15	0.66	0.98	0.66	5.90	9.83	6.23	1.31	1.64	0.33	0.33	0.98
KB-4	75.25	0.49	1.49	1.98	5.94	7.43	2.47	1.49	-	0.49	-	2.97
KB-5	77.29	0.87	0.87	0.44	6.55	7.86	3.06	0.44	0.87	-	-	1.75
KB-7	76.07	0.57	1.14	1.43	4.84	7.69	2.28	1.71	1.71	0.57	-	1.99
KB-8	70.39	0.43	1.72	2.58	9.01	8.15	3.43	0.43	1.29	-	0.43	2.14
KB-9	72.34	1.70	2.55	1.70	8.09	8.09	1.28	1.70	0.85	-	-	1.70
KB-12	80.14	0.70	1.04	0.70	3.49	6.27	2.79	1.39	1.04	-	0.70	1.74
KB-14	75.77	1.03	1.55	4.64	5.67	6.18	2.06	2.06	-	0.52	-	0.52
KB-17	73.08	-	1.10	2.75	9.34	7.69	3.29	0.55	-	0.55	-	1.65
KB-20	76.79	-	2.05	1.71	5.12	6.48	1.71	4.10	1.36	0.34	-	0.34
KB-23	70.05	1.52	1.01	2.04	7.61	11.68	2.04	1.52	1.01	0.51	-	1.01
KB-24	77.59	0.34	0.69	0.34	5.52	7.59	3.45	0.34	2.07	0.69	-	1.38
KB-25	75.34	-	0.34	0.69	7.53	7.53	5.48	0.69	1.37	0.34	-	0.69
KB-28	76.25	-	0.56	0.84	6.98	6.42	5.03	1.40	1.12	-	0.56	0.84
KB-32	74.76	2.43	0.48	1.46	7.28	5.34	3.89	0.48	0.48	0.48	-	2.92
KB-34	77.70	0.70	1.04	4.18	4.18	6.97	3.14	1.04	0.70	-	-	0.35
KB-35	79.48	-	0.58	0.29	2.89	9.25	1.16	2.60	1.73	0.29	-	1.73
KB-38	78.31	-	0.60	0.90	1.81	7.23	6.33	1.51	0.90	0.30	0.30	1.81

Lithic Fragments

Metamorphic lithic fragments comprise mainly phyllite and slate, followed by low grade schists and, occasionally, micaceous quartzite. They are subrounded to rounded in outline. Phyllite and slate fragments show intricately mixed microcrystalline silica, abundant tiny mica flaks and dark-brown ferruginous material. Moreover, phyllite fragments show strong preferred orientation of mica flaks. The schists consist almost entirely of muscovite crystals with parallel arrangement. Micaceous quartzite with schistose texture are high rank metamorphic rock fragments. The elongated quartz grains are separated by thin mica flaks.

The sedimentary lithic fragments are dominant in shale followed by siltstone and carbonate. The grains are mostly subangular to rounded. The fragments of shale are light brown to brown in colour, are ferruginous and show rounded outline. However, being softer the shale fragments are squeezed, occasionally, between the surrounding quartz grain forming pseudomatrix. The siltstone fragment shows subangular to subrounded quartz of silt size embedded in a matrix. Carbonate fragments exhibit fragment of iron-stained matrix. Volcanic lithic fragments are also present in a few thin section, which consist of felted masses of very small lath-like plagioclase crystals.

Heavy Minerals

Heavy minerals, though accessory constituents of sandstones, are useful guide to the nature of source rock. Heavy minerals include opaques, zircon, tourmaline, rutile, garnet and epidote in order of decreasing abundance. The concentration of opaque minerals is high and comprise mainly hematite and magnetite as subangular to rounded grains. Hematite show brown-black colour and high reddish birefringence, and magnetite show black colour and metallic lustre. Limonite was identified by its yellowish-brown colour and is present only in a few thin sections.

Next to opaque minerals, zircon occurs as colourless grains. Most of the zircon grains are subrounded to well rounded and a few are elongated with high relief and strong birefringence. Some grains contain inclusions of ferrugineous minerals. Tourmaline occurs as subrounded to rounded grain which includes brown, green, yellowish-brown, yellowish-green varieties in order of decreasing abundance. Rutile is present as elongated and subangular to subrounded grains of reddish-brown colour. Garnet occurs as colourless subangular grains.

CLASSIFICATION OF SANDSTONE

Sandstones have been classified by several workers (Krynine, 1948; Pettijohn, 1948, 1954; Shrock, 1946, 1948; and Rodgers, 1950) and their status reviewed by Klein (1963), McBride (1963), Okada (1971) and Pettijohn (1972). The most commonly accepted classification is that of Folk's (1980) based on the composition of the detrital framework constituents.

According to Folk's (1980) classification scheme, all the essential detrital constituents viz. quartz (Q), feldspar (F) and lithic fragments (L), were recalculated to 100 percent excluding clay, matrix, cements, heavy minerals, mica flaks etc., and allotted them to one of the three following poles:

Q-pole: all types of quartz including metaquartzite

F-pole: all single feldspar grains both fresh and altered plus granite and gneiss fragments

L-pole: all other lithic fragments plus chert grain

The sample points from all the three locations lie in the 'sub-arkosic' field of QFL triangular diagram of Folk (1980). Thus, the sandstones of Katrol Formation of Keera Hill are 'sub-arkosic' in nature.

PETROFACIES AND TECTONIC SETTING

Dickinson and Rich (1972) were the first to use certain parameters to define petrofacies. For this certain key proportions of detrital grains were used. Dickinson (1985) classified sandstones on the basis of their characteristic petrofacies which is primarily controlled by the tectonic setting of the provenance, which is reflected by the detrital modes of sandstone suites. Petrofacies analysis of sandstones can furnish vital clues regarding the provenance and its tectonic setup and the source rock composition. These are used to interpret the tectono-sedimentary evolution of geo-province and its sedimentary cover (Dickinson *et al.*, 1983; Mack, 1984; Schwab, 1991; Graham *et al.*, 1993; Cox and Lowe, 1995).

The analysis requires counting of framework grains and calculating various parameters, i.e., Qm, Qp, Qt, P, K, F, Lsm, Lvm, Lm, Ls, Lv, Lt (Table 7) as given by Ingersoll and Suczek (1979) and Dickinson (1985). The parameters were recalculated to 100 percent and used in the five triangular diagrams QtFL, QmFLt, QmPK, QpLvmLsm and LmLvLs for provenance study. Intrabasinal grains (Zuffa, 1980) and heavy minerals were ignored. Similarly, extrabasinal carbonate grains or detrital limeclasts were also not considered along with other lithic fragments. Such grains show vastly different geochemical response during weathering and diagenesis and may be confused easily with intrabasinal carbonate grains (intraclasts, bioclasts, oolits, peloids).

For compositional field characteristic of different provenance, five triangular diagram were employed i.e. QtFL, QmFLt, QmPK (Dickinson, 1985) and QpLvmLsm, LmLvLs (Ingersoll and Suczek, 1979; Suczek and Ingersoll, 1985) for present study.

Dickinson's (1985) QtFL and QmFLt diagram is based on maturity and source rock, respectively. Three classes were distinguished. They are: (i) Continental block, for which sediment source are on shield and platforms or in faulted basement blocks; (ii) magmatic arc, for which the source are within active arc orogen of island arc or active continental margins; (iii) recycled orogen, for which source are deformed and uplifted stratal sequence in subduction zones along collision orogens, or within foreland fold-thrust belts.

The circum-pacific volcano-plutonic is the main provenance class of QmPK diagram of Dickinson, and is based on mineral grains. Ingersoll and Suczek's triangular diagrams QpLvmLsm and LmLvLs emphasise on lithic population, which are divided into four provenance field classes (i) rifted continental margin (ii) magmatic arc (iii) suture belt (iv) mixed magmatic arc and subduction complex. But subsequently, Suczek and Ingersoll (1985) omitted the field for rifted continental margin from LmLvLs diagram, because it lay just within the field for suture belt source and so it was not found useful for provenance discrimination.

The relative proportion of detrital framework grains plotted on the triangular diagrams effectively discriminate among the variety of plate tectonic setting and provide a powerful tool in the interpretation of plate interactions in the geological past (Ingersoll, 1983).

Table 7 : Counted framework grains and calculated parameters

Framework grains (Folk, 1980)

CQ	:	Common Quartz
VQ	:	Vein Quartz
RMQ	:	Recrystallized Metamorphic Quartz
SMQ	:	Streached Metamorphic Quartz
PF	:	Plagioclase Feldspar
KF	:	Potassium Feldspar
M	:	Mica
H	:	Heavy Minerals
C	:	Chert
MLF	:	Metamorphic Lithic Fragments
SLF	:	Sedimentary Lithic Fragments
VLF	:	Volcanic Lithic Fragments

Calculated Parameters (Ingersoll and Suczek, 1979; Dickinson, 1985)

Qm	:	Monocrystalline Quartz Grains (= CQ + VQ)
Qp	:	Polycrystalline Quartz Grains (= RMQ + SMQ +C)
Qt	:	Total Quartzos Grains (= Qm + Qp)
P	:	Plagioclase Feldspar Grains (= PF)
K	:	Potassium Feldspar Grains (= KF)
F	:	Total Feldspar Grains (= P + K)
Lm	:	Metamorphic Lithic Fragments (= MLF)
Lv	:	Volcanic Lithic Fragments (= VLF)
Ls	:	Sedimentary Lithic Fragments (= SLF)
L	:	Total Unstable Lithic Fragments (= Lm+Lv+Ls)
Lt	:	Total Lithic Fragments (= L+C)
Lvm	:	Volcanic and Metavolcanic Lithic Fragments (= Lv)
Lsm	:	Sedimentary, Metasedimentary and Metamorphic Lithic Fragments (= Lm+Ls)

Location-I

The percentage of QtFL parameters of the sandstones are 79.87 to 88.46% (average 84.23%), 10.49 to 18.79% (average 14.66%), 0.43 to 1.88% (average 1.11%) respectively (Table 8). Their plot on the QtFL diagram lies along the Qt-F leg nearer Qt pole, in the continental block provenance (Figure 10A).

The QmFLt parameters for these sandstones is rich in Qm, 77.52 to 85.66% (average 80.72%), followed by feldspar (F), 10.49 to 18.79% (average 14.66%), and total lithic (Lt), 2.17 to 8.96% (average 4.62%) (Table 8). These data plot in continental block provenance near Qm pole (Figure 10B).

The QmPK parameter values are 80.49 to 88.67% (average 84.64%), 6.22 to 12.84% (average 9.06%), 3.27 to 9.52% (average 6.30%), respectively (Table 8). These percentages indicate that Qm is more abundant than plagioclase feldspar (P) and potassium feldspars (K), therefore, these sandstone plot nearer the Qm pole along the Qm-P leg, which suggest that the maturity/stability increasing from continental block provenance (Figure 10C).

The percentage values of QpLvmLsm range 53.33 to 92.86% (average 74.35%), 0 to 9.09% (average 1.52%) and 6.67 to 40.00% (average 24.13%), respectively (Table 8). The volcanic/metavolcanic lithic fragments (Lvm), in low percentage are present only in a few sandstone samples. These recalculated parameters plot on the polycrystalline- total sedimentary, meta-sedimentary and metamorphic lithic fragment (Qp-Lsm) leg near Qp pole, indicating that rifted continental margin, only one sample plots in the collision orogen field (Figure 10D).

In LmLvLs parameter, sedimentary lithic (Ls) dominate at 37.50 to 100% (average 69.57%), followed by lesser metamorphic lithic (Lm), 0 to 62.50% (average 27.96%) and volcanic lithic (Lv), 0 to 16.67% (average 2.47%) (Table 8). In this case data plot in LmLvLs diagram close to Ls pole on/along the metamorphic-sedimentary lithic fragments (Lm-Ls) leg in the suture belts and mixed magmatic arc and subduction complex. However, average value plot in the suture belts field (Figure 10E).

Location-II

In Location II sandstone samples, Qt is the dominant member of QtFL parameters and the values are from 80.58 to 85.93% (average 83.72%), 10.55 to 18.75% (average 15.41%) and 0.35 to 1.47% (average 0.87%), respectively (Table 8). These data plot in the continental block provenance in QtFL diagram near Qt pole along Qt-F leg (Figure 11A).

The QmFLt parameter values vary from 77.08 to 82.41% (average 79.80%), 10.55 to 18.75% (average 15.40%) and 2.78 to 8.33% (average 4.80%), respectively (Table 8). These data plot near Qm pole in continental block provenance (Figure 11B).

The values of QmPK parameters vary between 80.43 to 88.65% (average 83.84%), 5.65 to 11.67% (average 8.39%) and 3.24 to 11.62% (average 7.77%), respectively (Table 8). The data plot near Qm pole, indicating an increasing maturity/stability from continental block provenance (Figure 11C).

The parameters QpLvmLsm of the sandstones give a high Qp, 66.67 to 93.75% (average 81.16%) followed by Lsm, 6.25 to 33.33% (average 17.96%) and Lvm, 0 to 7.14% (average 0.88%) (Table 8). The QpLvmLsm diagram shows that most of the samples plot in the field of rifted continental margin along Qp-Lsm leg near Qp pole (Figure 11D).

The values for LmLvLs are 0 to 66.67% (average 28.80%), 0 to 20.00% (average 2.42%) and 33.33 to 100.00% (average 68.78%), respectively (Table 8). They plot in the suture belt along Lm-Ls leg, only one sample plots on Lv-Ls leg near Ls pole. Thus, the average values plot in the field of suture belt (Figure 11E).

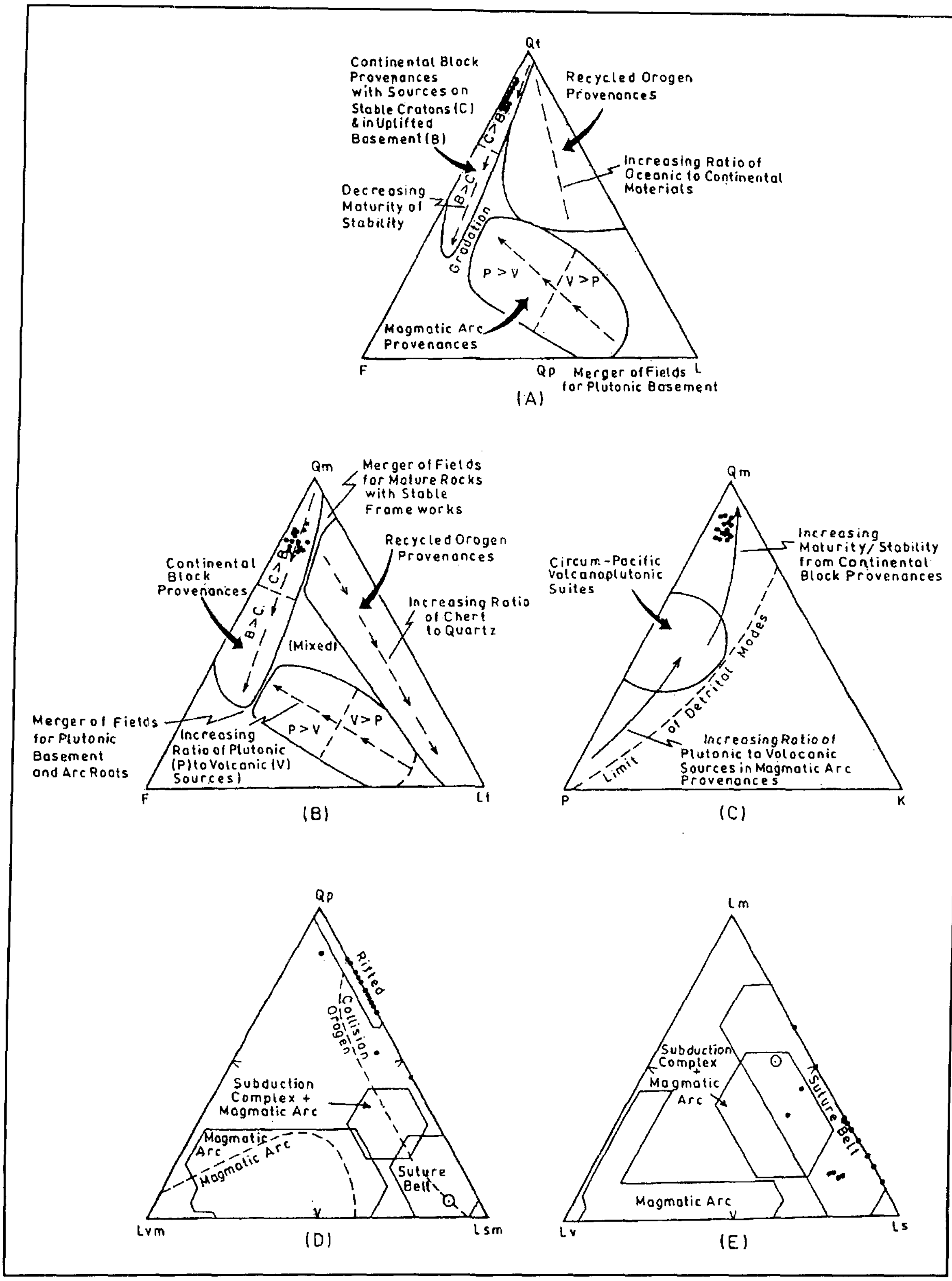


Figure 10: Tectono-provenance discriminating diagrams for Katrol Sandstone (Location I), Keera hill, Kachchh. The Provenance fields Figure 10A, 10B, 10C, and figure 10D, 10E and their sub-division are as per Dickinson (1985) and Ingersoll and Suczek (1979) respectively.

Table 8: Percentage of framework modes of Katrol Formation (Upper Jurassic) Keera Hill Sandstone, Kachchh (Based on the classification of Dickinson, 1985; Ingersoll and Suczek, 1979)

Sample No.	Q_t	F	L	Q_m	F	L_t	Q_m	P	K	Q_p	L_{vm}	L_{sm}	L_m	L_v	L_s
LOCATION-I															
KM-1	85.22	12.90	1.88	83.07	12.90	4.03	86.56	8.68	4.76	53.33	6.67	40.00	41.67	8.33	50.00
KM-2	84.65	14.17	1.18	80.71	14.17	5.12	85.06	6.22	8.72	76.92	-	23.08	28.57	-	71.43
KM-4	87.98	10.93	1.09	85.52	10.93	3.55	88.67	7.08	4.25	69.23	-	30.77	33.33	-	66.67
KM-7	82.49	16.59	0.92	79.26	16.59	4.15	82.69	11.54	5.77	77.78	-	22.22	16.67	-	83.33
KM-9	84.26	13.77	1.97	82.62	13.77	3.61	85.72	9.86	4.42	45.45	-	54.55	62.50	-	37.50
KM-10	83.33	14.94	1.73	79.02	14.94	6.04	84.10	9.17	6.73	71.43	-	28.57	31.25	-	68.75
KM-11	85.15	14.24	0.61	80.91	14.24	4.85	85.03	8.28	6.69	93.33	-	6.67	11.11	-	88.89
KM-12	82.53	16.73	0.74	78.81	16.73	4.46	82.49	12.84	4.67	83.33	-	16.67	20.00	-	80.00
KM-13	82.52	16.26	1.22	78.46	16.26	5.28	82.83	9.01	8.16	76.92	-	23.08	20.00	-	80.00
KM-15	86.57	11.94	1.49	79.10	11.94	8.96	86.88	7.38	5.74	83.33	-	16.67	25.00	-	75.00
KM-17	85.77	13.50	0.73	82.48	13.50	4.01	85.93	7.23	6.84	81.82	-	18.18	25.00	-	75.00
KM-19	84.01	14.87	1.11	79.93	14.87	5.20	84.31	10.59	5.10	78.57	-	21.43	28.57	-	71.43
KM-20	84.21	14.80	0.99	81.58	14.80	3.62	84.64	7.85	7.51	72.73	-	27.27	33.33	-	66.67
KM-21	88.11	10.49	1.40	85.66	10.49	3.85	89.09	7.64	3.27	63.64	9.09	27.27	12.50	12.50	75.00
KM-22	83.81	15.32	0.87	81.79	15.32	2.89	84.23	11.90	3.87	70.00	-	30.00	33.33	-	66.67
KM-25	81.15	17.62	1.23	77.87	17.62	4.51	81.54	12.02	6.44	72.73	-	27.27	50.00	-	50.00
KM-29	83.67	15.31	1.02	77.55	15.31	7.14	83.52	9.89	6.59	85.72	7.14	7.14	14.29	14.29	71.42
KM-31	81.59	17.69	0.72	80.14	17.69	2.17	81.92	9.23	8.85	66.67	-	33.33	50.00	-	50.00
KM-35	79.87	18.79	1.34	77.52	18.79	3.69	80.49	10.45	9.06	63.64	9.09	27.27	33.33	16.67	50.00
KM-39	88.46	11.11	0.43	82.91	11.11	5.98	88.18	6.36	5.46	92.86	-	7.14	-	-	100.00
KM-40	83.45	15.85	0.70	80.28	15.85	3.87	83.52	6.96	9.52	81.82	-	18.18	16.67	-	83.33
LOCATION-II															
KS-2	85.15	14.49	0.36	80.07	14.49	5.44	84.68	8.81	6.51	93.33	-	6.67	33.33	-	66.67
KS-4	80.58	18.45	0.97	77.67	18.45	3.88	80.81	7.57	11.62	75.00	-	25.00	25.00	-	75.00
KS-5	83.88	14.65	1.47	80.95	14.65	4.40	84.67	8.43	6.90	66.67	-	33.33	80.00	-	20.00
KS-7	82.93	16.72	0.35	77.70	16.72	5.58	82.29	8.12	9.59	93.75	-	6.25	-	-	100.00
KS-9	81.65	17.23	1.12	79.03	17.23	3.74	82.10	11.67	6.23	70.00	-	30.00	60.00	-	40.00
KS-10	85.16	13.55	1.29	80.64	13.55	5.81	85.62	6.16	8.22	77.78	-	22.22	33.33	-	66.67
KS-13	83.11	15.88	1.01	78.72	15.88	5.40	83.21	11.07	5.72	81.25	6.25	12.50	16.67	16.67	66.66
KS-14	82.73	16.87	0.40	79.52	16.87	3.61	82.50	7.92	9.58	88.89	-	11.11	25.00	-	75.00

KS-16	83.33	15.87	0.80	81.35	15.87	2.78	83.67	7.35	8.98	71.43	-	28.57	33.33	-	66.67
KS-20	84.36	15.17	0.47	81.99	15.17	2.84	84.39	7.32	8.29	83.33	-	16.67	-	-	100.00
KS-22	82.62	16.22	1.16	79.15	16.22	4.63	83.00	8.50	8.50	75.00	-	25.00	20.00	-	80.00
KS-25	80.83	18.75	0.42	77.08	18.75	4.17	80.43	10.00	9.57	90.00	-	10.00	33.33	-	66.67
KS-26	80.99	18.25	0.76	76.81	18.25	4.94	80.80	10.80	8.40	84.62	-	15.38	-	-	100.00
KS-29	82.31	17.01	0.68	79.93	17.01	3.06	82.46	9.47	8.07	77.78	-	22.22	25.00	-	75.00
KS-30	85.93	12.96	1.11	81.85	12.96	5.19	86.33	7.03	6.64	78.57	7.14	14.29	-	16.67	83.33
KS-31	85.78	12.75	1.47	78.92	12.75	8.33	86.10	8.02	5.88	82.35	5.88	11.77	20.00	20.00	60.00
KS-33	81.13	18.07	0.80	77.91	18.07	4.02	81.17	10.04	8.79	80.00	-	20.00	66.67	-	33.33
KS-34	85.11	13.83	1.06	80.50	13.83	5.67	85.34	6.39	8.27	81.25	-	18.75	25.00	-	75.00
KS-35	85.88	12.94	1.18	82.35	12.94	4.71	86.42	7.41	6.17	75.00	-	25.00	50.00	-	50.00
KS-36	84.95	14.42	0.63	81.82	14.42	3.76	85.02	8.79	6.19	83.33	-	16.67	25.00	-	75.00
KS-38	85.09	14.29	0.62	79.19	14.29	6.52	84.72	5.65	9.63	90.48	-	9.52	28.57	-	71.43
KS-40	88.44	10.55	1.01	82.41	10.55	7.04	88.65	8.11	3.24	85.71	-	14.29	33.33	-	66.67
LOCATION-III															
KB-2	80.57	16.96	2.47	77.39	16.96	5.65	82.02	11.24	6.74	56.25	6.25	37.50	45.45	9.10	45.45
KB-4	85.34	14.14	0.52	80.10	14.14	5.76	85.00	8.33	6.67	90.90	-	9.10	-	-	100.00
KB-5	83.94	15.14	0.92	82.11	15.14	2.75	84.43	8.49	7.08	66.67	-	33.33	66.67	-	33.33
KB-7	84.53	13.09	2.38	80.06	13.09	6.85	85.94	8.63	5.43	65.22	-	34.78	42.86	-	57.14
KB-8	80.00	18.18	1.82	75.00	18.18	6.82	80.49	9.27	10.24	73.33	6.67	20.00	60.00	20.00	20.00
KB-9	82.46	16.67	0.87	76.31	16.67	7.02	82.08	8.96	8.96	87.50	-	12.50	33.33	-	66.67
KB-12	87.96	10.22	1.82	84.67	10.22	5.11	89.23	6.92	3.85	64.29	14.28	21.43	33.33	22.22	44.45
KB-14	87.30	12.17	0.53	78.84	12.17	8.99	86.63	6.97	6.40	94.12	-	5.88	-	-	100.00
KB-17	81.50	17.92	0.58	76.88	17.92	5.20	81.10	8.54	10.36	88.89	-	11.11	-	-	100.00
KB-20	86.41	11.85	1.74	78.40	11.85	9.75	86.87	7.34	5.79	82.14	-	17.86	23.53	-	76.47
KB-23	78.53	19.90	1.57	73.82	19.90	6.28	78.77	12.85	8.38	75.00	-	25.00	33.33	-	66.67
KB-24	83.33	13.77	2.90	81.88	13.77	4.35	85.61	8.33	6.06	33.33	-	66.67	66.67	-	33.33
KB-25	82.12	16.06	1.82	80.29	16.06	3.65	83.34	8.33	8.33	50.00	-	50.00	57.14	-	42.86
KB-28	83.98	14.24	1.78	81.01	14.24	4.76	85.05	7.16	7.79	62.50	12.50	25.00	36.36	18.18	45.46
KB-32	85.42	13.54	1.04	82.81	13.54	3.65	85.94	5.95	8.11	71.43	-	28.57	33.33	-	66.67
KB-34	87.73	11.55	0.72	81.23	11.55	7.22	87.55	7.78	4.67	90.00	-	10.00	40.00	-	60.00
KB-35	85.42	12.50	2.08	81.85	12.50	5.65	86.75	10.09	3.16	63.16	-	36.84	37.50	-	62.50
KB-38	88.52	9.84	1.64	85.24	9.84	4.92	89.65	8.28	2.07	66.67	6.67	26.66	30.00	10.00	60.00

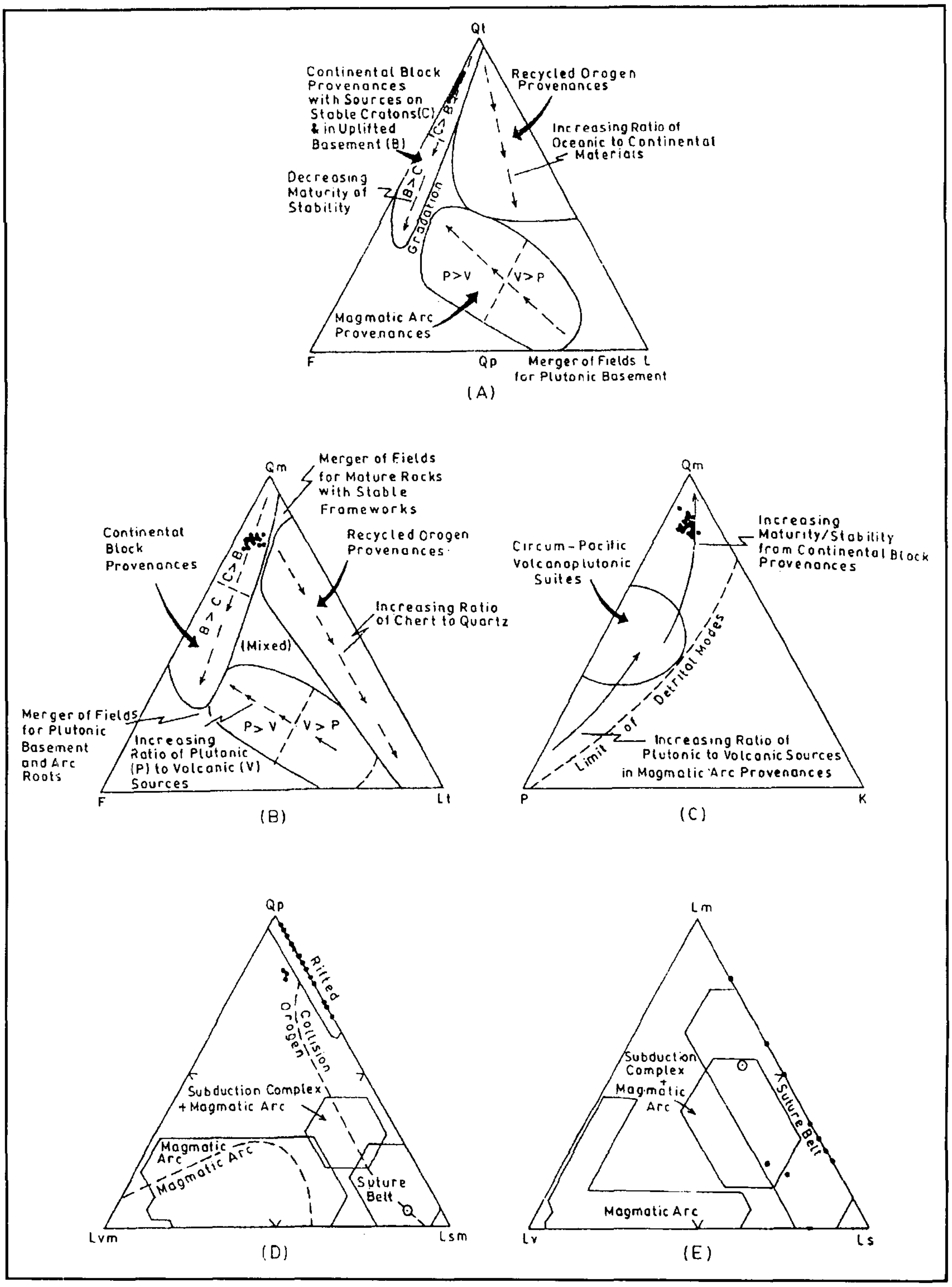


Figure 11: Tectono-provenance discriminating diagrams for Katrol Sandstone (Location I), Keera hill, Kachchh. The Provenance fields Figure 11A, 11B, 11C, and figure 11D, 11E and their sub-division are as per Dickinson (1985) and Ingersoll and Suczek (1979) respectively.

Location-III

The values of the parameters QtFL of the sandstones are 78.53 to 88.52% (average 84.17%), 9.84 to 19.90% (average 14.32%), 0.52 to 2.90% (average 1.51%), respectively (Table 8). In the QtFL diagram they plot in the continental block provenance near Qt pole, along Qt-F leg (Figure 12A).

The parameters QmFLt have monocrystalline quartz (Qm) as dominant with 73.82% to 85.24% (average 79.88%), followed by feldspar (F), 9.84% to 19.90% (average 14.32%), and total lithic (Lt) 2.75% to 8.99% (average 5.80%) (Table 8). Thus the data plot in the field of continental block near Qm pole (Figure 12B).

The parameters Qm = 78.77 to 89.65% (average 84.80%) followed by plagioclase feldspar (P) = 5.95 to 12.85% (average 8.53%) and potassium feldspar (K) = 2.07 to 10.36% (average 6.67%) (Table 8). On the triangular diagram these data plot near Qm pole. This suggests increasing maturity/stability from continental block provenance (Figure 12C).

The parameters QpLvmLsm have values as 33.33 to 94.12% (average 71.19%), 0 to 14.28% (average 2.58%) and 5.88 to 66.67% (average 26.23%), respectively (Table 8). In the QpLvmLsm diagram, the entire sandstones plot in the rifted continental margin and collision orogen along Qp-Lsm leg. However, the average values plot in the rifted continental margin (Figure 12D).

The percentage values of parameters LmLvLs range 0 to 66.67% (average 35.53%), 0 to 22.22% (average 4.42%) and 20.00 to 100.00% (average 60.05%), respectively (Table 8). On LmLvLs diagram, they plot along the Lm-Ls leg are in the field of suture belts (Figure 12E).

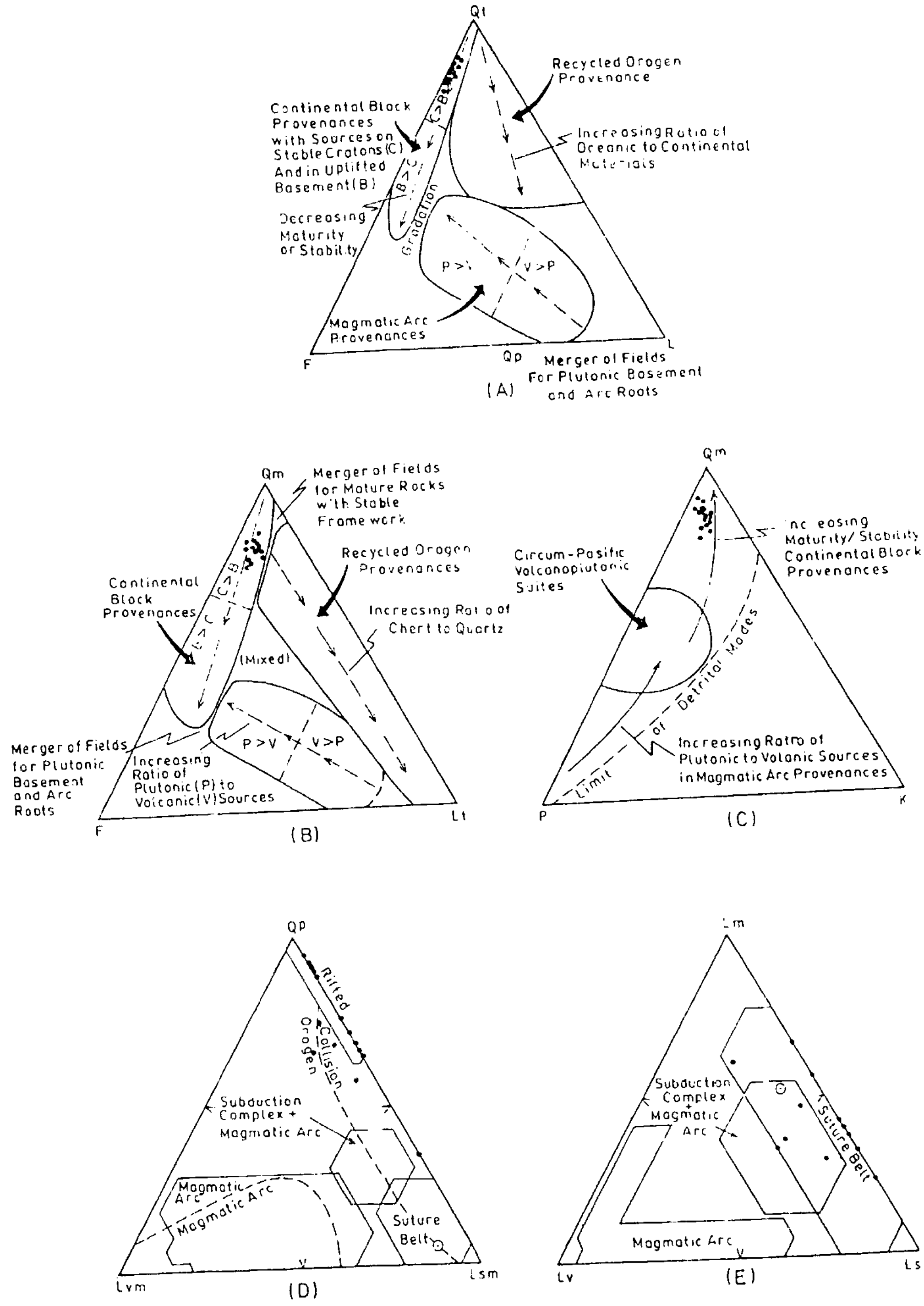


Figure 12: Tectono-provenance discriminating diagrams for Katrol Sandstone (Location I), Keera hill, Kachchh. The Provenance fields Figure 12A, 12B, 12C, and figure 12D, 12E and their sub-division are as per Dickinson (1985) and Ingersoll and Suczek (1979) respectively.

PROVENANCE

The dominant detrital mode of quartz in the sandstones is monocrystalline (average 76.57%) followed by polycrystalline (average 2.51%). Their source could be plutonic or volcanic igneous rocks, metamorphic rocks or sedimentary rocks. The distinction between plutonic igneous and metamorphic monocrystalline quartz is based on difference in inclusions, shape, and extinction. Some workers find it difficult to apply these criteria because the attributes like shape and extinction show wide variations in the same rock and an assessment of these is very subjective. However, dominance of monocrysalline and nonundulose grains suggests mainly plutonic and high rank metamorphic source rock.

Perthitic feldspars are indicative of slow cooling and hence characteristic of plutonic source. Orthoclase and microcline are also derived from acid plutonic rocks. Absence of zoned plagioclase are point to non volcanic sources.

Rock fragments are among the most informative of all the detrital components. When studied carefully they provide an idea of provenance. The rock fragments in the sandstones include phyllite, slate, shale, siltstone, chert, schist, carbonate and volcanic lithics which indicate derivation from low rank metamorphic rocks and carbonate terrains and volcanic assemblages.

Micas are generally, divided from schist and gneisses, plutonic igneous rocks, and also volcanic sources. Mica forms a very small percentage of the sandstones and hence do not throw much light on their provenance.

The suit of heavy minerals including opaques, zircon, tourmaline, rutile, garnet and epidote indicate acid igneous – metamorphic source. The rounded rutile, tourmaline and zircon are indicative of reworked source for these sandstones.

On the basis of above description, it can be concluded that the source rocks for Katrol Sandstone include granites, granite- gneisses, low and high grade metamorphic rocks and some basic rocks. These rocks most probably got eroded and weathered from parts of Aravalli and Delhi Folded Belt. Their palaeo-current pattern studied by Balagopal and Srivastava (1975) suggests that the provenance of Katrol sandstone was located in the south, which was in all probability south-west extension of Aravalli Delhi Folded Belt (ADFB), now covered partly below the post-Jurassic rocks of Kathiawar and partly under the Arabian Sea. The tectonic style of Aravalli- Delhi folded belt makes it *collage* of recycled orogen and basement uplift provenance. It is expected that sandstone detrital modes derived from would plot in a recycled orogen provenance. But most of the petrofacies QtFL, QmFLt, QmPK plot in the continental block provenance. In addition to this, the QpLvmLsm and LmLvLs diagrams indicate sediment were contributed from rifted continental margin, suture belt and mixed magmetic arc and subduction complex. This is accordance with ADFB tectonic evolution and mode of origin of Kachchh Basin. False signature of continental block provenance may be the result of several factors, which have modified the original composition of the detritus in one way or the other. The major controls on the detritus composition are exerted by palaeo-climate, transport, sediment recycling and diagenesis.

CHAPTER 8

DIAGENESIS OF SANDSTONE

INTRODUCTION

The term diagenesis was first given by Von Gumbel (1868) for a set of transformations, independent of metamorphism, which makes a compact rock out of the fresh sediment (Segonzac, 1968). Diagenesis includes all physico-chemical, biochemical and physical process modifying sediments between deposition and lithification at low temperature and pressure, characteristic of surface and near-surface environments (Chilingar *et al.*, 1967). Diagenesis is controlled by many factors and process, such as, texture, detrital composition, environment of deposition and associated lithologies. On a regional scale, diagenesis is controlled by tectonic setting of basin by virtue of geothermal gradient, rate and extent of basin subsidence. The diagenetic process in sandstone can broadly be categorized into physical and chemical diagenesis and these processes operate simultaneously towards establishing physical adjustment to surrounding stress field and an equilibrium chemical composition.

Physical diagenesis includes mechanical and chemical compaction, as studied by several workers (Taylor, 1950; Fuchtbauer, 1967, 1974; Chilingarian, 1983). Mechanical compaction is the bulk volume reduction, induced by lithostatic stress, characterized by reorientation and repacking of competent (brittle) grains by local fracturing or along cleavage of brittle grains and by plastic deformation of ductile grains. Chemical compaction is caused by dissolution of framework grains along grain of contacts (Fuchtbauer, 1967), generally induced by lithostatic stress. They are characterized by intergranular pressure solution.

The chemical diagenesis includes reaction leading to chemical dissolution, corrosion and cementation. These reactions may start just after the deposition of sand and is controlled by oxidation and reduction of sediment-water and atmosphere interface. Chemical potential of sediments and pore water chemistry play an important role in removal of various unstable phases and precipitation of new stable phases in the diagenetic regime.

The diagenetic processes play significant role in reducing, enhancing or retaining the porosity of sandstones (Wolf and Chilingarian, 1976). Porosity can be defined as percentage of all void spaces in a sand or sandstone. Reduction in porosity results from combination of compaction and cementation (Scherer, 1987; Houseknecht, 1987; Pate, 1989; Ehrenberg, 1989; Lundegard, 1992; Ehrenberg, 1995). Some workers studied these process separately (Wilson and McBride, 1988; McBride *et al.* 1991; Houseknecht, 1988).

The diagenetic study of sandstones of Katrol Formation in (Keera Hill) Kachchh includes compaction, cementation, depth of burial and their respective role in the evolution of porosity.

ANALYTICAL METHOD

The study is based on thin section examination of fifty-one sandstone samples, taken from three different locations of the area under study. About two hundred fifty to three hundred points were counted from each thin section along linear traverses, at grid point spacing. It also included nature of contacts, number of contact, cements and porosity.

COMPACTION

The compaction study of the sandstones two packing parameters taken in account are nature of grain contact (Taylor, 1950) and contact index (Pettijohn *et al.*, 1987). The later is the average number of contacts per grain. The nature of grain contact were classified and counted as floating, point, long, concavo-convex and sutured as observed in thin section. Floating grains are those that do not show any contact with the adjacent ones. The point contact appears as a point, the long contact appears as straight line, concavo-convex contact appears as interpenetrative curve and sutured contact appears as irregular interpenetrative zig-zag line. The nature of contacts and number of contacts per grain were counted along linear traverse, at grid point spacing and their percentage determined in sandstone samples from each location.

The Location-I sandstones shows dominance of long contact (Figure 13A). Their percentage ranges between 6.36% to 51.97% (average 37.56%), followed by point contact which ranges between 25.81% to 48.21% (average 33.38%), floating grain ranges between 2.23% to 41.88% (average 21.18%), concavo-convex contact between 0 to 14.67% (average 7.15%) and sutured contact between 0 to 2.88% (average 0.73%). There may be 0, 1, 2, 3, 4 or 5 grains in contact around a single grain, which average at 29.78%, 28.20%, 23.16%, 11.64%, 5.56% and 1.66%, respectively. The contact index values range from 0.82% to 2.81% (average 1.89%) (Table 9).

The nature of grain contact of Location-II sandstone reveal that point contact and floating grains are dominant (Figure 13B). They range from 27.07% to 56.04% (average 41.95%) and 17.09 to 66.16% (average 40.35%), respectively, followed by long contact grains which range from 0 to 27.27% (average 15.86%). The percentage of concavo-convex grain contact range from 0 to 5.71% (average 1.84%) while the sutured contacts are absent. The grain with 0, 1, 2, 3, 4 or 5 grain contacts average at 49.13%, 32.72%, 12.18%, 4.41%, 1.41% and 0.15%, respectively. The contact index values range from 0.78 to 1.83 (averages 1.26) (Table 9).

The sandstones of Location-III have maximum percentage of floating grains which range 19.67 to 80.85% (average 44.72%) (Figure 13C). The percentage of point, long and concavo-convex contacts range from 17.02 to 55.74% (average 35.98%), 2.13 to 29.32% (average 17.55%) and 0 to 5.05% (average 1.70%), respectively. The sutured contacts are almost negligible averaging only at 0.05%.

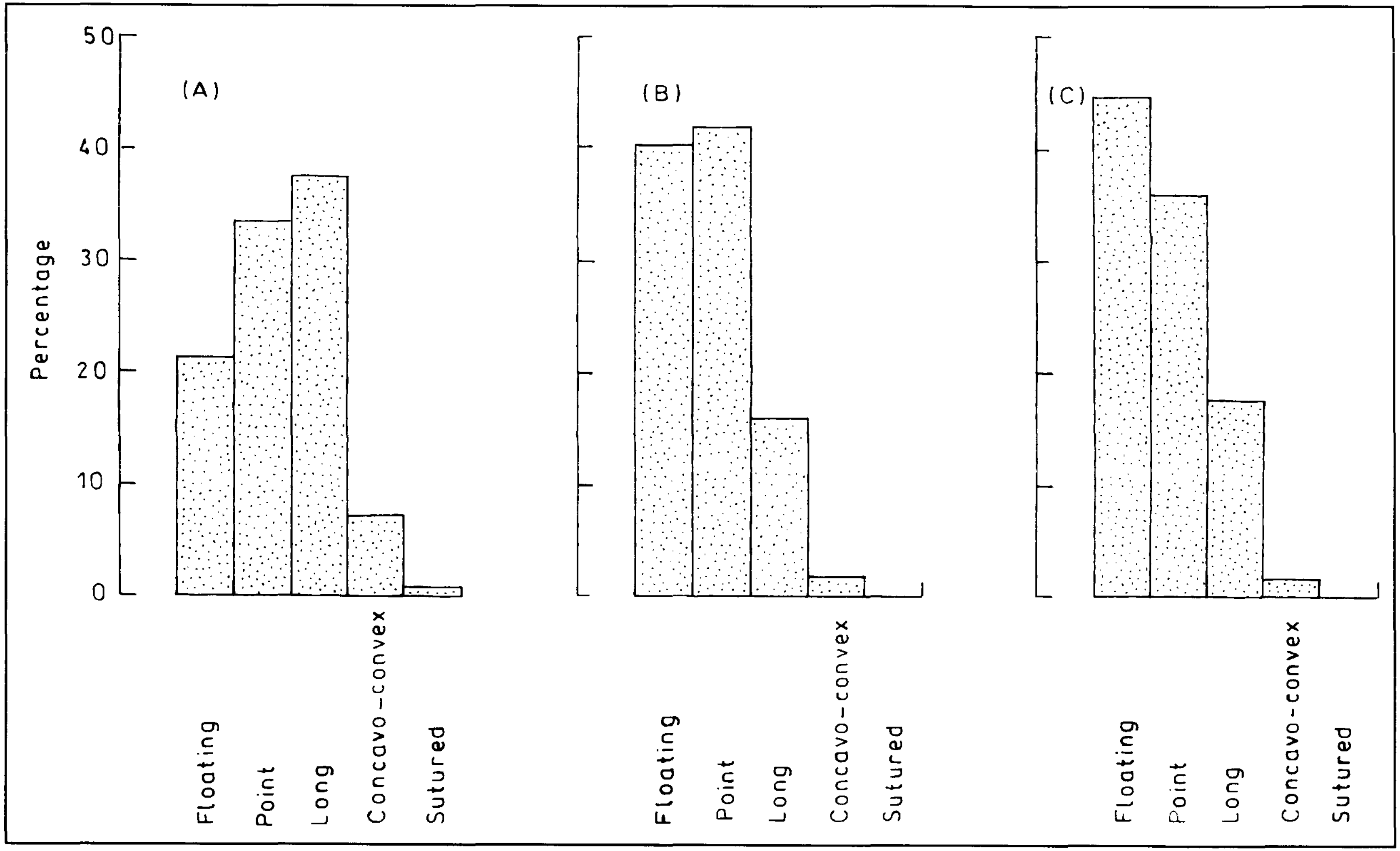


Figure 13: Histograms showing types of grain contacts in Katrol Sandstone, Keera hill, Kachchh.

Table 9: Compaction parameters of Katrol Formation (Upper Jurassic), Keera Hill Sandstone, Kachchh

Sample No.	Nature of Contacts per Grain Points					Number of Contacts per Grain Points						Contact Index
	Floating	Point	Long	Concavo-Convex	Sutured	0	1	2	3	4	5	
Location-I												
KM-1	10.79	25.90	46.76	13.67	2.88	20.83	25.00	27.78	16.67	6.94	2.78	2.22
KM-2	8.69	31.16	46.38	12.32	1.45	17.91	28.36	25.37	14.92	8.96	4.48	2.32
KM-4	3.23	31.18	48.92	13.98	2.69	7.90	18.42	27.63	30.26	11.84	3.95	2.81
KM-7	29.70	31.68	28.72	8.91	0.99	41.67	30.55	18.05	5.56	4.17	-	1.50
KM-10	3.81	29.35	50.54	14.67	1.63	8.64	22.22	34.57	20.99	11.11	2.47	2.61
KM-12	70.00	23.64	6.36	-	-	74.76	20.39	2.91	1.94	-	-	0.82
KM-15	8.75	32.50	51.25	7.50	-	17.07	31.71	26.83	12.19	7.32	4.88	2.25
KM-17	8.66	27.56	51.97	10.24	1.57	18.33	23.33	25.00	21.67	6.67	5.00	2.40
KM-19	15.87	45.24	32.54	6.35	-	27.03	31.08	24.32	8.11	6.76	2.70	1.94
KM-20	14.40	34.40	47.20	4.00	-	24.00	32.00	26.67	10.67	6.66	-	1.94
KM-22	12.85	38.54	42.46	5.03	1.12	22.33	33.01	24.27	10.68	7.77	1.94	2.04
KM-25	29.25	39.62	28.30	2.83	-	39.24	30.38	26.58	3.80	-	-	1.44
KM-29	36.84	34.21	26.32	2.63	-	47.19	31.46	15.73	4.50	1.12	-	1.30
KM-31	5.38	25.81	58.06	10.75	-	10.64	25.53	38.30	17.02	8.51	-	2.37
KM-35	48.33	30.83	19.17	1.67	-	56.31	31.07	10.68	1.94	-	-	1.08
KM-39	41.88	37.61	18.80	1.71	-	52.69	30.11	11.83	3.22	2.15	-	1.22
KM-40	11.61	48.21	34.82	5.36	-	19.70	34.85	27.27	13.64	4.54	-	1.98
Average	21.18	33.38	37.56	7.15	0.73	29.78	28.20	23.16	11.64	5.56	1.66	1.89
Location-II												
KS-2	36.95	43.48	16.67	2.90	-	45.54	34.82	16.96	2.68	-	-	1.26
KS-4	17.58	56.04	24.18	2.20	-	28.57	37.50	14.29	12.50	5.36	1.78	1.83
KS-5	53.57	39.29	5.95	1.19	-	57.69	32.05	8.98	1.28	-	-	1.03
KS-9	57.65	36.94	5.41	-	-	64.65	29.29	5.05	1.01	-	-	0.92
KS-10	31.43	42.86	20.00	5.71	-	42.31	36.54	11.54	5.77	3.84	-	1.42
KS-13	28.18	42.73	27.27	1.82	-	37.35	36.14	19.28	7.23	-	-	1.46
KS-14	41.96	33.93	20.54	3.57	-	51.65	30.77	12.09	4.39	1.10	-	1.22
KS-22	43.75	39.84	16.41	-	-	52.83	31.13	11.32	3.78	0.94	-	1.18
KS-25	52.34	38.32	9.34	-	-	59.57	29.79	7.45	3.19	-	-	1.04
KS-26	53.44	38.93	7.63	-	-	59.32	30.51	9.32	0.85	-	-	1.01

KS-30	36.62	40.84	19.72	2.82	-	45.62	37.72	11.40	3.51	1.75	-	1.28
KS-31	41.91	45.71	11.43	0.95	-	51.76	30.59	12.95	3.53	1.18	-	1.21
KS-33	42.31	48.46	7.69	1.54	-	55.00	26.00	13.00	4.00	1.00	1.00	1.23
KS-34	17.09	47.86	30.77	4.28	-	24.69	43.21	22.22	7.41	2.47	-	1.69
KS-35	50.00	32.86	14.28	2.86	-	57.38	31.15	8.19	3.28	-	-	1.07
KS-36	66.16	27.07	6.77	-	-	73.95	23.53	2.52	-	-	-	0.78
KS-38	31.25	50.00	17.19	1.56	-	39.21	40.20	16.67	2.94	0.98	-	1.36
KS-40	24.14	50.00	24.14	1.72	-	37.33	28.00	16.00	12.00	6.67	-	1.72
Average	40.35	41.95	15.86	1.84	-	49.13	32.72	12.18	4.41	1.41	0.15	1.26
Location-III												
KB-2	50.72	28.99	17.39	2.90	-	61.95	21.24	12.39	3.54	0.88	-	1.22
KB-4	34.48	45.69	18.10	1.73	-	45.98	26.43	22.99	3.45	1.15	-	1.37
KB-5	35.36	38.38	21.21	5.05	-	49.29	23.94	18.31	4.23	2.82	1.41	1.41
KB-7	24.81	42.86	29.32	3.01	-	35.49	31.18	22.58	8.60	2.15	-	1.60
KB-8	39.58	42.71	16.67	1.04	-	50.00	31.58	11.84	5.26	1.32	-	1.26
KB-9	80.85	17.02	2.13	-	-	85.39	10.12	3.37	1.12	-	-	0.70
KB-14	49.51	30.69	17.82	1.98	-	59.52	22.62	14.29	3.57	-	-	1.11
KB-17	55.04	28.44	15.60	0.92	-	63.83	23.41	9.57	3.19	-	-	1.02
KB-20	70.97	22.58	6.45	-	-	73.95	21.85	4.20	-	-	-	0.80
KB-23	36.36	35.06	24.68	3.90	-	45.16	38.71	9.68	4.84	1.61	-	1.29
KB-24	60.74	28.15	11.11	-	-	64.57	29.13	6.30	-	-	-	0.91
KB-25	55.37	29.75	14.88	-	-	60.36	31.53	7.21	0.90	-	-	0.98
KB-28	41.49	43.09	14.36	1.06	-	49.06	33.96	15.09	1.89	-	-	1.19
KB-32	31.15	40.16	25.41	3.28	-	41.30	33.70	18.48	5.43	1.09	-	1.41
KB-34	29.41	46.32	22.79	0.74	0.74	38.46	33.65	22.12	4.81	0.96	-	1.46
KB-38	19.67	55.74	22.95	1.64	-	25.81	49.46	16.13	6.45	2.15	-	1.59
Average	44.72	35.98	17.55	1.70	0.05	53.13	28.91	13.41	3.58	0.88	0.09	1.20

The 0, 1, 2, 3, 4 or 5 grain contacts average at 53.13%, 28.91%, 13.41%, 3.58%, 0.88% and 0.09%, respectively. Their contact index values vary from 0.70 to 1.60 (average 1.20) (Table 9).

On the area level, sandstone exhibit dominantly floating grains and point contact followed by long and concavo- convex contact (Plate III). Floating and point contacts, varying between 3.23% to 80.85% (average 35.42%) and 17.02% to 56.04% (average 37.10%), respectively. The long contact grains range from 2.13% to 58.06% (average 23.65%) and concavo-convex ones range from 0 to 14.67% (average 3.57%). The sutured contact grains being least common between 0 to 2.88% (average 0.26%). The grain with 0, 1, 2, 3, 4 or 5 number of contacts average at 44.02%, 29.94%, 16.25%, 6.54%, 2.62% and 0.63% respectively. Their contact index values ranging from 0.70 to 2.81 (average 1.45) (Table 9).

The average contact index value for freshly deposited beach sand are around 0.79 (Atkins and McBride, 1992) while in the sandstones under study around 1.45. The high percentages of floating grains and point contacts and low value of contact index indicate that the sandstones were subjected to little compaction and pressure-solution as a result of either shallow burial or early stage cementation. The high minus-cement porosity (average 33.06%) too suggests early stage cementation. The large-scale mechanical and chemical compaction would be resisted because of open framework and pervasive development of cements which, normally, takes place just after the deposition of sediments. The presence of long contact suggests that the compaction of sandstone took place in early stages, when grains rotated and adjusted themselves to the boundaries of the adjacent grains. The low proportion of concavo-convex and sutured contact indicates limited grain dissolution due to chemical compaction.

CEMENT AND MATRIX

The chemically precipitated material, which forms cement, is an important constituent of sandstones. Cementation is the occlusion of intergranular volume by the precipitation of authigenic minerals directly related to reduction of bulk volume. These minerals precipitate under suitable physico-chemical conditions. Introduction of cement affects both porosity and permeability of the rock and also stabilize framework structure.

In the studied sandstones, six types of cement have been identified and described including calcite, iron oxide, silica, dolomite, clay and matrix in order of decreasing abundance.

Calcite Cement

Calcite cement is present in all the samples of sandstone and occupy intergranular pore spaces. The calcite cement occurs in two forms—microcrystalline calcite (micrite) and sparry calcite. The microcrystalline calcite cements are present in a few samples as pervasive pore filling. The sparry calcite, probably a late stage cement, shows both pervasive and patchy distribution. The pervasive type shows well developed mosaic of microspar. Those with patchy development have large crystals with well-developed cleavage planes. In some thin sections, small calcite crystals exhibit subequant interlocking boundary within large calcite crystals, and in a few calcite cements are also found corroding and replacing quartz along grain boundaries and also the feldspars along grain boundaries and cleavage planes causing little modification of original textures (Plate IVA). Such modifications are not extensive in view of the patchy distribution of calcite cement.

The calcite cement in sandstones of Location-I range from 1.52% to 20.00% (average 11.91%), of Location-II from 2.81% to 18.10% (average 10.58%) and of

Location-III from 3.51% to 20.76% (average 14.12%). On area level calcite cement ranges from 1.52% to 20.00% (average 12.13%) (Table 10).

The larger sized crystals of calcite indicate slower rate of precipitation from dilute solutions rather than rapid crystallization (Dapples, 1971). The precipitation of microcrystalline calcite cement probably took place at shallow depths as evidenced by open framework and entrapped iron-strained clay matrix. Later, during burial diagenesis, microcrystalline calcite cements were replaced by sparry calcite in meteoric hydrologic regime along the interface of zone of aeration and saturation. The presence of oversized pore-filled calcite cement might be due to destruction and leaching of labile framework grain, possibly feldspar, which may have taken place at sediment-water interface.

Iron Oxide Cement

Iron oxide cements are present in three different forms (i) as pervasive pore filling which is most common (ii) as occasional patches and (iii) as thin coating around detrital grain boundary which is the least abundant.

The pervasive development of iron oxide cement, dark brown in colour, is associated with high percentage of floating grains and oversized pores. In many instances, pervasive iron-oxide cement corrode and replace detrital grains along cleavage and grain boundaries, causing loss of morphology and instead forming protrusions, embayments and notches. The oversized iron oxide filled pores, either due to destruction or corrosion and complete digestion of labile framework grains, possibly, feldspar. The light brown to brown patchy iron-oxide distribution suggests either aborted cementation or dissolution during uplift.

The iron-oxide cement coating around detrital grains and interparticle pore spaces, present in a few samples, is due to release of iron oxide through the disintegration of unstable ferromagnesian minerals during weathering and pedogenic processes.

The iron-oxide also replaces calcite cement which indicates late stage cementation (Plate IVB). The iron oxide cement is perhaps derived from weathering and leaching of ferromagnesian minerals of overlying Deccan Traps. The iron oxide cement in Location-I sandstone ranges from 2.94% to 21.55% (average 9.56%), Location-II sandstone ranges from 1.63% to 23.53% (average 10.88%) and Location-III sandstone ranges from 3.09% to 23.77% (average 11.28%). On area level, it ranges from 1.63% to 23.77% (average 10.56%) (Table 10).

Silica Cement

The silica cement occurs in small amount, generally in the form of quartz overgrowth, which shows optical continuity with detrital quartz grains. The overgrowth develops by direct precipitation of silica from aqueous solution and grow into the intergranular spaces (Plate IVC). In a few cases silica cement consists of chalcedonic and microcrystalline quartz in the pores between the grains. Such cements comprise radiating microfibrous shaped quartz aggregates. Microcrystalline quartz occur as subequant randomly oriented, interlooking grains and with pin point birefringence. The presence of small amount of silica cement can be attributed to limited compaction of sandstone, thereby causing very little pressure solution, which is the most important indigenous source of silica. But other sources could be descending meteoric water saturated with silica.

Depth of burial and geothermal gradient has not been found sufficient for reaching the 'silica window' (McBride, 1989). The merger quartz overgrowth could be due to intraformational release of silica during replacement and corrosion of feldspars. The percentage of silica cement in Location-I range from 0 to 3.78% (average 1.87%), Location-II from 0 to 3.77% (average 1.12%) and Location-III from 0 to 4.92% (average 1.72%). The gross value for silica cement range from 0 to 4.92% (average 1.56%) (Table 10).

Table 10: Diagenetic phase of the Keera Hill Sandstone of Katrol Formation (Upper Jurassic), Kachchh
TC = Total Cement, EOP = Existing Optical Porosity, MCP = Minus Cement Porosity,
COPL = Compactional Porosity Loss, CEPL = Cementational Porosity Loss

Sample No.	Detrital Grains	C E M E N T S							POROSITY		POROSITY LOSS	
		Calcite	Iron Oxide	Silica	Matrix	Clay	Dolomite	TC	EOP	MCP	COPL	CEPL
Location-I												
KM-1	65.15	1.52	15.15	3.03	2.27	-	-	21.97	12.88	34.85	15.57	18.55
KM-2	72.17	13.40	6.19	2.06	1.03	1.03	-	23.71	4.12	27.83	23.79	18.06
KM-4	70.18	19.30	4.38	0.88	1.75	-	-	26.31	3.51	29.82	21.63	20.61
KM-7	64.28	1.02	16.33	1.02	1.02	2.04	-	21.43	14.29	35.72	14.43	18.33
KM-10	71.62	13.51	3.38	2.70	3.38	1.35	-	24.32	4.06	28.38	23.20	18.68
KM-12	69.61	13.73	2.94	-	-	-	11.76	28.43	1.96	30.39	20.98	22.47
KM-15	70.83	18.75	3.13	-	1.04	2.08	-	25.00	4.17	29.17	22.34	19.41
KM-17	74.12	11.89	5.59	2.80	-	-	1.40	21.68	4.20	25.88	25.79	16.09
KM-19	63.45	17.24	11.72	2.07	-	0.69	-	31.72	4.83	36.55	13.31	27.50
KM-20	67.31	14.42	7.69	2.89	-	-	-	25.00	7.69	32.69	18.28	20.43
KM-22	73.21	16.07	4.46	1.79	1.79	-	-	24.11	2.68	26.79	24.87	18.11
KM-25	66.09	20.00	9.56	2.61	-	-	-	32.17	1.74	33.91	16.78	26.76
KM-29	70.69	4.31	21.55	-	0.86	-	-	26.72	2.59	29.31	22.19	20.79
KM-31	62.26	1.89	16.98	3.78	-	-	-	22.65	15.09	37.74	11.66	20.00
KM-35	71.43	5.71	14.29	0.95	1.91	0.95	-	23.81	4.76	28.57	23.00	18.33
KM-39	68.03	14.75	9.84	3.28	-	-	-	27.87	4.10	31.97	19.15	22.53
KM-40	65.42	14.95	9.35	1.87	-	-	-	26.17	8.41	34.58	15.92	22.00
Average	68.58	11.91	9.56	1.87	0.88	0.48	0.77	25.47	5.95	31.41	19.58	20.50
Location-II												
KS-2	68.69	8.08	18.18	1.01	-	-	-	27.27	4.04	31.31	19.93	21.83
KS-4	70.73	7.32	17.07	1.22	-	-	-	25.61	3.66	29.27	22.23	19.92
KS-5	67.96	5.83	21.36	1.94	-	-	-	29.13	2.91	32.04	19.07	23.57
KS-9	60.38	3.77	20.75	3.77	1.89	1.89	-	32.07	7.55	39.62	8.91	29.21
KS-10	69.83	18.10	5.17	0.86	-	-	-	24.13	6.04	30.17	21.24	19.00
KS-13	62.30	12.29	13.93	-	2.46	1.64	-	30.32	7.38	37.70	11.71	26.77
KS-14	60.16	9.75	7.32	2.44	1.63	0.81	1.63	23.58	16.26	39.84	8.57	21.55
KS-22	70.09	2.81	18.69	1.87	0.93	1.87	-	26.17	3.74	29.91	21.52	20.54

KS-25	63.41	13.82	1.63	-	-	-	11.38	26.83	9.76	36.59	13.26	23.27
KS-26	60.36	16.22	2.70	0.90	-	-	12.61	32.43	7.21	39.64	8.88	29.54
KS-30	65.79	10.53	5.26	1.75	-	0.88	-	18.42	15.79	34.21	16.40	15.39
KS-31	73.68	7.37	10.53	-	-	-	2.11	20.01	6.31	26.32	25.35	14.93
KS-33	66.37	11.50	7.97	1.77	-	-	8.85	30.09	3.54	33.63	17.13	24.93
KS-34	65.38	15.38	3.85	0.77	-	3.08	-	23.08	11.54	34.62	15.87	19.41
KS-35	67.01	14.43	4.13	-	-	2.06	-	20.62	12.37	32.99	17.92	16.92
KS-36	63.73	4.90	23.53	1.96	-	-	-	30.39	5.88	36.27	13.69	26.23
KS-38	73.53	11.77	9.80	-	1.96	-	-	23.53	2.94	26.47	25.20	17.60
KS-40	72.44	16.54	3.94	-	2.36	-	-	22.84	4.72	27.56	24.07	17.34
Average	66.77	10.58	10.88	1.12	0.63	0.68	2.03	15.92	7.31	33.23	17.27	21.55
Location-III												
KB-2	65.79	3.51	13.16	2.63	3.51	0.88	-	23.69	10.52	34.21	16.41	19.79
KB-4	67.80	16.95	4.24	2.54	1.69	0.85	-	26.27	5.93	32.20	18.88	21.30
KB-5	59.43	20.76	6.60	2.83	1.89	-	-	32.08	8.49	40.57	7.46	29.68
KB-7	66.67	20.00	6.67	1.90	-	-	-	28.57	4.76	33.33	17.51	23.56
KB-8	68.75	18.75	4.17	2.08	-	-	-	25.00	6.25	31.25	20.00	20.00
KB-9	70.10	20.62	3.09	1.03	-	-	-	24.74	5.16	29.90	21.54	19.41
KB-14	65.57	2.47	23.77	4.92	-	-	-	31.15	3.28	34.43	16.13	26.11
KB-17	63.53	12.94	18.82	-	-	-	-	31.76	4.71	36.47	13.42	27.49
KB-20	64.45	8.89	20.00	2.22	-	-	-	31.11	4.44	35.55	14.66	26.55
KB-23	69.66	15.73	3.37	1.12	-	-	-	20.22	10.12	30.34	21.04	15.96
KB-24	62.39	14.68	7.34	1.83	3.67	-	-	27.52	10.09	37.61	11.84	24.26
KB-25	61.54	17.31	15.39	0.96	1.92	-	-	35.58	2.88	38.46	10.62	31.80
KB-28	65.62	12.50	15.63	-	2.08	-	-	30.21	4.17	34.38	16.18	25.32
KB-32	64.70	14.12	9.41	3.53	-	-	-	27.06	8.24	35.30	14.99	23.00
KB-34	71.17	7.21	17.12	-	-	-	-	24.33	4.50	28.83	22.72	18.80
KB-38	60.19	19.42	11.65	-	-	-	-	31.07	8.74	39.81	8.62	28.39
Average	65.46	14.12	11.28	1.72	0.92	0.11	-	28.15	6.39	34.54	15.75	23.84

Dolomite Cement

Dolomite as cement occurs only in a few samples of sandstone under study. They were identified on the through staining test and certain optical properties. It occurs as of isolated crystals, in patches and as pervasive which forms rhombic crystals (Plate VA). Dolomite, in general, is found to replace calcite. It has brown stains and is probably 'ferroan'. The dolomite rhombs are euhedral to subhedral and abut against framework grains. Such rhombs also exhibit sharply defined *zoning with iron-rich and iron-poor composition alternating.* Dolomitization normally require, increase in Mg concentration, high temperature and evaporation, high CO_2 pressure, high Mg/Ca ratio, lower SO_4 and organic acid effects (Tucker and Wright, 1991). Occasionally dolomite cement may form due to incursion of surface water, rich in Mg ions, which mix with circulating basinal pore water (Tucker, 1986; Morse and Wright, 1990). The dolomite cement is found only in a few thin sections from rocks of Locations-I and II but absent in those of Location-III. The amount of dolomite cement in Location-I range from 0 to 11.76% (average 0.77%) and in Location-II from 0 to 12.61% (average 2.03%). On the area level they range from 0 to 12.61% (averages 0.98%) (Table 10).

Clay Cement

The clay cement is present in minor amount. It is mainly Kaolinte and occurs as intergranular microcrystalline aggregate of both allogenic and authigenic origin. The allogenic Kaolinte is very common and show irregular aggregate of plates with rugged outlines, often conforming with the adjacent coarser detrital grains, a result of deformation during compaction. Authigenic Kaolinite present only in few samples and shows well-developed rosettes crystal, not deformed by compaction. They are the alteration products of feldspar and mica grains during diagenesis. The amount of Kaolinite cement in Location-I range from 0 to 2.08%, in Location-II from 0 to 3.08% (average 0.68%) and in Location-III from 0 to

0.88% (average 0.11%). On area level their range is from 0 to 3.08% (average 0.43%) (Table 10).

Matrix

In majority of sandstones, detrital silt and chert mixed with fine grained muscovite and clay are present in varying amount. In some, this matrix is stained by iron oxide. Most of the matrix material is syndepositional, and hence pore filling. The amount of matrix present in Location-I range from 0 to 3.38% (average 0.88%), Location-II from 0 to 2.46% (average 0.63%) and Location-III from 0 to 3.67% (average 0.92%). On the area level the amount of matrix range from 0 to 3.67% (average 0.81%) (Table 10). Matrix exerts influence on diagenetic process by supplying chemical entities and bulk properties, such as porosity and permeability by pore occlusion. The very low amount of matrix seen, probably, decanted from infiltrating muddy pore water.

POROSITY EVOLUTION AND DEPTH OF BURIAL

Porosity are void spaces which could be primary if intergranular or secondary if due to dissolution of cement, microfracture in detrital grains and micropores in altered feldspars. The existing optical porosity (EOP) in Location-I sandstone range from 1.74% to 15.09% (average 5.95%), Location-II from 2.91% to 16.26% (average 7.31%) and Location-III from 2.88% to 10.52% (average 6.39%). On the area level the EOP range from 1.74% to 16.26% (average 6.57%) (Table 10). The samples with pervasive cemented of calcite and iron-oxide show sign of development of secondary porosity involving dissolution and leaching (Plate VB). Most sandstones have low primary porosity due to pores profusely cemented with calcite and iron oxide, indicative of very early stage cementation. The oversize pores filled with cement are also observed to be coated by iron-stain.

Minus-cement porosity (MCP) is defined as volume percentage of existing optical porosity (EOP) plus total cement. This provides insight into depositional porosity. Sandstones show minus cement porosity (MCP) values ranging from 26.79% to 37.74% (average 31.42%) in Location-I, 26.47% to 39.84% (average 33.23%) in Location-II and 28.83% to 40.57% (average 34.54%) in Location-III, respectively. The area level study indicates that the MCP values range from 26.47% to 40.57% (average 33.03%) (Table 10).

The high percentage of MCP indicates open framework which suggests that sandstones were probably cemented soon after deposition before significant burial or low mechanical compaction ensued.

Several works on the basis of laboratory and field experiments have eatimated the depth of burial of sandstones by plotting average MCP values on standard burial depth versus MCP graphs (McCulloh 1967; Lapinskaya and Preshpyakova 1971; Atwater and Miller 1965; Selley 1978). These plots were used to estimate the depth of burial of the sandstones of Katrol Formation. The depth of burial obtained for these rocks at Location-I range from 987.90m to 1758.62m (average 1259.77m), for Location-II from 806.45m to 1275.86m (average 979.94m) and for Location-III from 705.64m to 1000.00m (average 811.65m). The overall depth of burial is from 705.64m to 1758.62m (average 1017.12m) (Table 11).

Table 11: Interpreted depth of burial of Keera Hill Sandstone of Katrol Formation, Kachchh

Depth of burial vs MCP graph employed	Interpreted depth of burial in meter		
	Location-I	**Location-II**	**Location-III**
McCulloh (1967)	1085.67m	837.46m	713.39m
Lapinskaya *et al.* (1971)	987.90m	806.45m	705.64m
Selley (1978)	1206.89m	1000.00m	827.58m
Atwater & Miller (1965)	1758.62m	1275.00m	1000.00m
Average	**1259.77m**	**979.94m**	**811.65m**

The evolution of porosity and the relative roles of compaction and cementation have been quantitatively worked out by using formula and variation diagram given by Lundegard (1992) and Ehrenberg (1995).

$$COPL = Pi - [\{(100 - Pi) \times MCP\} / (100 - MCP)] \quad \text{(i)}$$

$$CEPL = (Pi - COPL) \times (TC / MCP) \quad \text{(ii)}$$

Where COPL is the porosity loss due to compaction, Pi is initial porosity, MCP is minus-cement porosity, TC is total cement and CEPL is porosity loss due to cementation.

The sandstones, which are mainly fine-to medium-grained, moderately sorted to moderately well sorted and have subarkosic framework composition, and are deposited in shallow marine conditions, qualify to have Pi of 45 percent (Atkins and McBride, 1992), which we have used here as an assumed initial porosity to resolve equation (i) and (ii) and for the plot COPL verse CEPL.

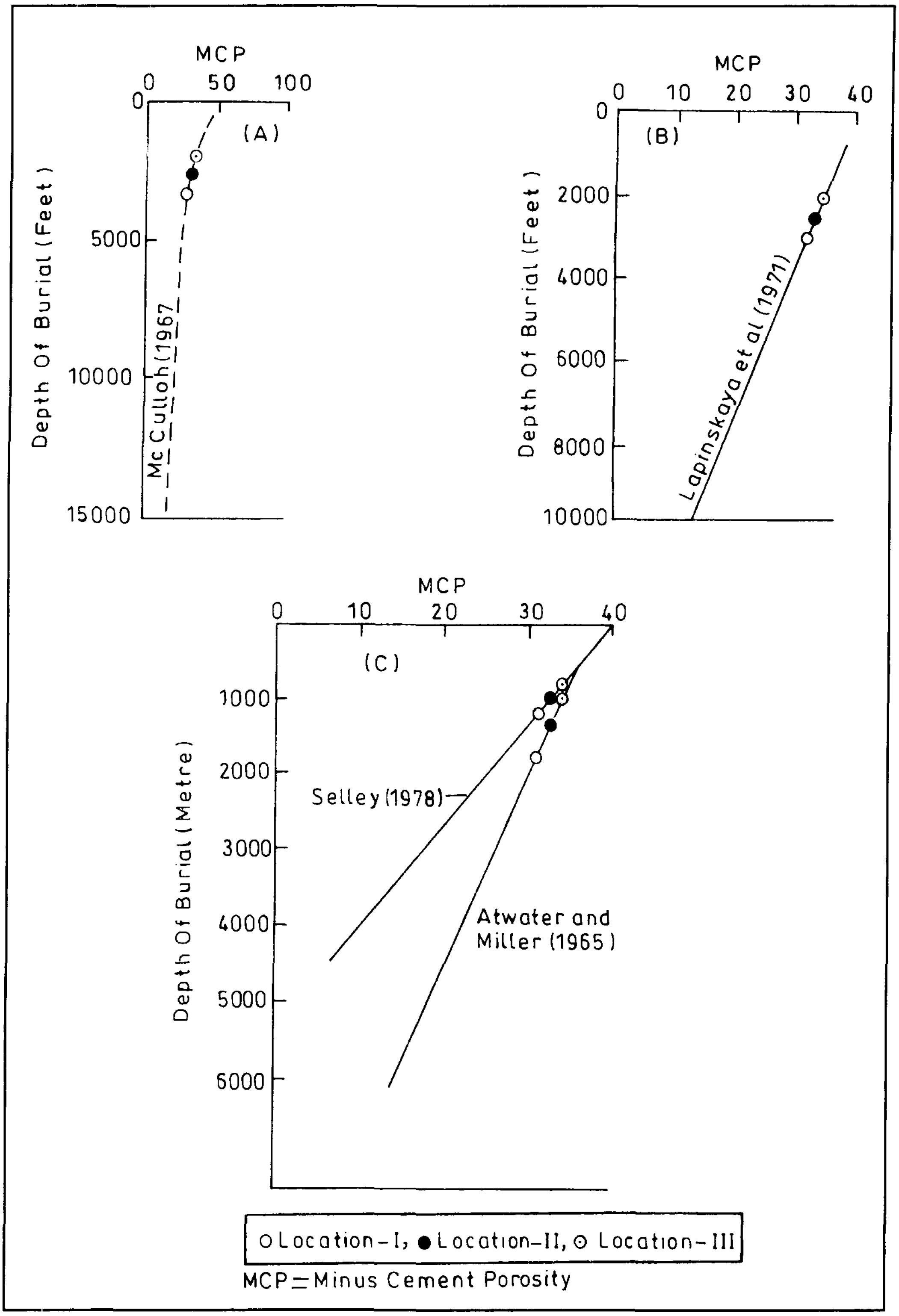


Figure 14: Relationship between average minus-cement porosity and depth of burial of Katrol Sandstone, Keera hill, Kachchh

The values of COPL and CEPL plotted on variation diagram given by Lundegard (1992) suggests that cementation played a dominant role in the porosity reduction. Therefore, compaction seem to be a secondary factor in the porosity reduction. The porosity loss due to compaction in Location-I, Location-II, Location-III sandstone average at 19.58%, 17.29%, 15.75% and due to cementation 20.50%, 21.55%, 23.84%, respectively (Table 10). The overall porosity loss due to compaction averages at 17.57% and due to cementation 21.92% (Figure 15).

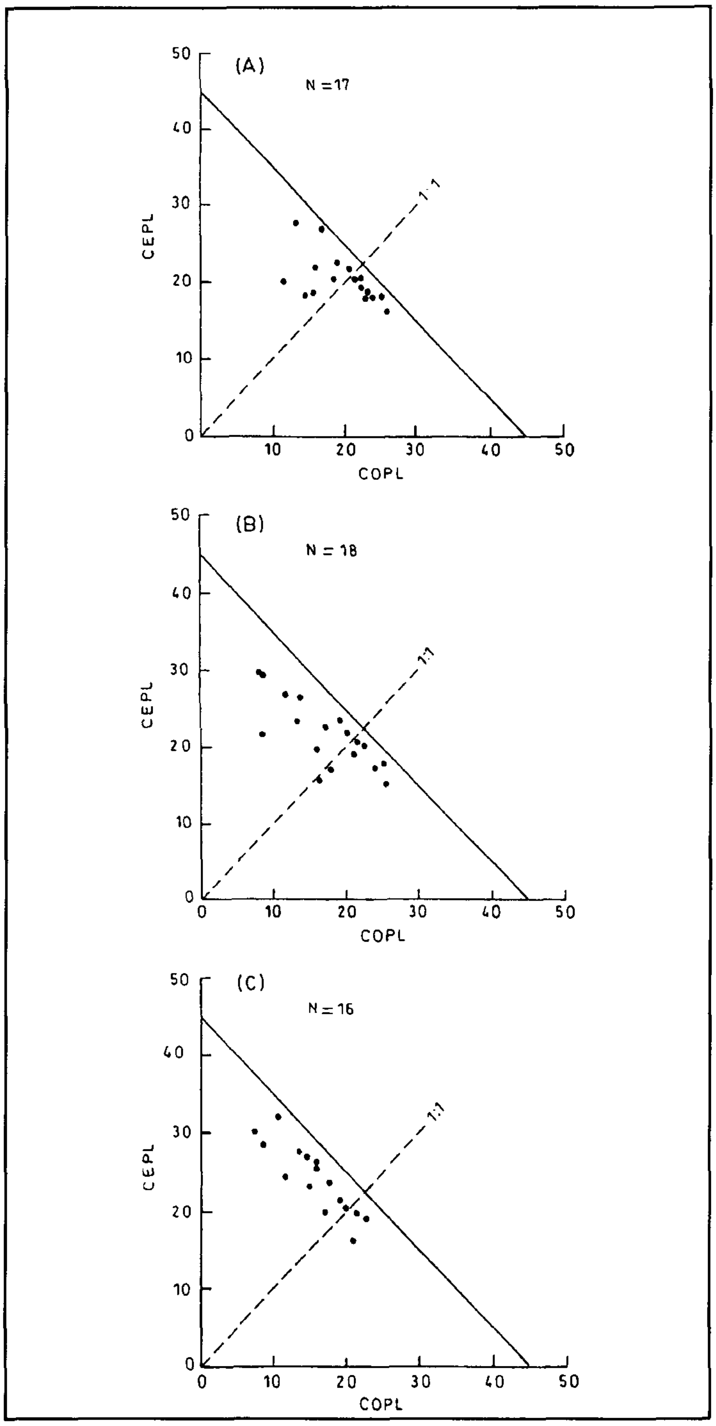


Figure 15: Porosity evolution and relative importance of compactional and cementational porosity loss Katrol Sandstone, Keera hill, Kachchh

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Plate I

Figures

1. *Reophax* aff. *R. suevica* Franke X88
2. *Ammobaculites coprolithiformis* (Schwager) X145
3. *Ammobaculites nanogyrus* Nagy and Seidenkrantz X120
4. *Trocholina conosimilis* Subbatina and Srivastava X137
5. *Spirillina polygyrata* Guembel X250
6. *Nodosaria simplex* (Terquem) X190
7. *Pyramidulina hortensis* (Terquem) X410
8. *Frondicularia* cf. *F. involuta* Terquem X120
9. *Lenticulina dilectaformis* Subbatina and Srivastava X114
10: *Lenticulina discipiens* (Wisniowski) X122
11. *Lenticulina ectypa* (Loeblich and Tappan) X125
12. *Lenticulina muensteri* (Roemer) X129
13. *Lenticulina quenstedti* (Guembel) X128
14. *Lenticulina subalata* (Reuss) X110
15. *Lenticulina* aff. *L. subalata* (Reuss) X168
16. *Lenticulina tricarinella* (Reuss) X122

Plate-I

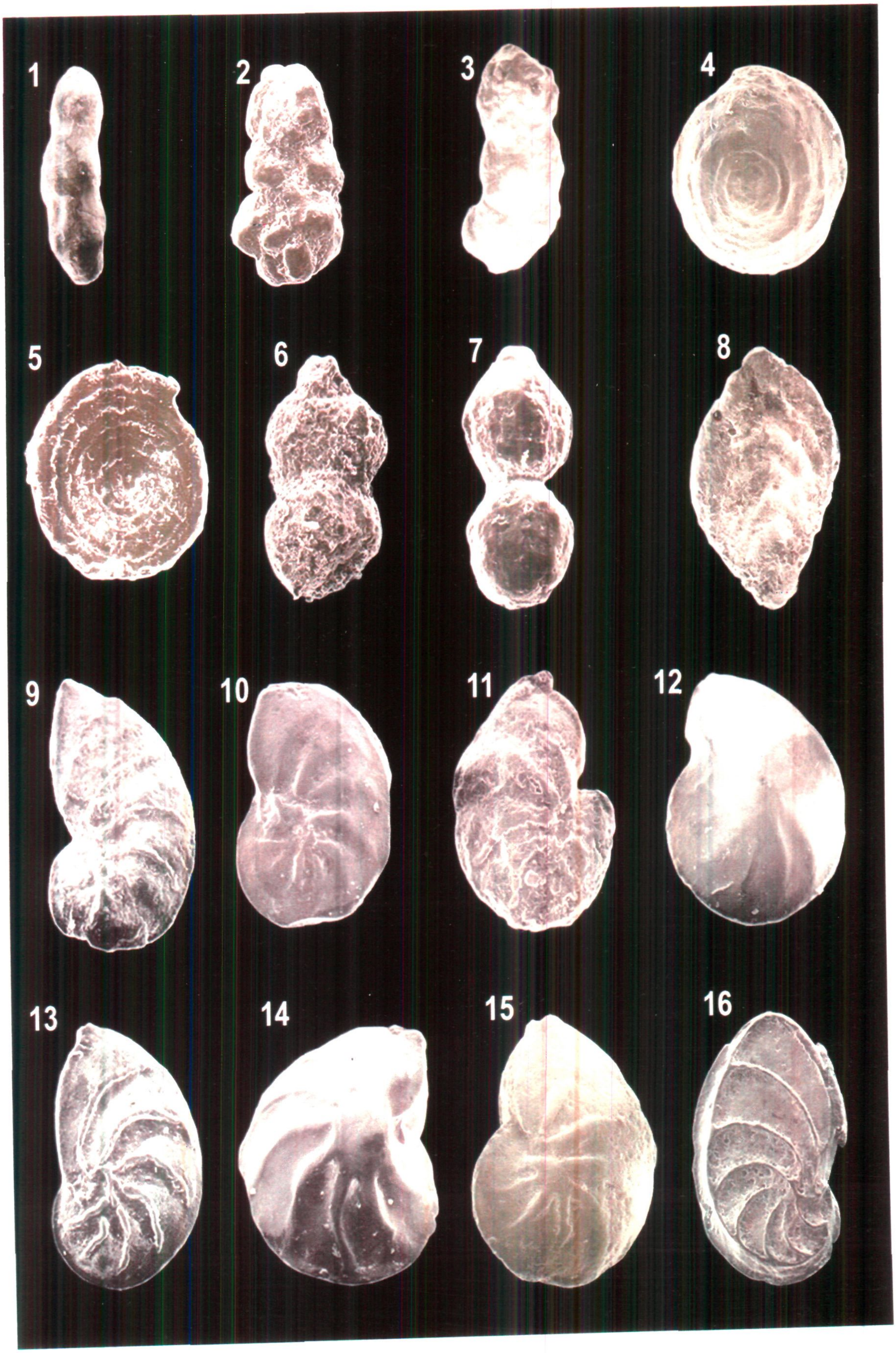


Plate II

Figures

17. *Lenticulina varians* (Bornemann) X116
18. *Lenticulina* sp. Indet. X253
19. *Saracenaria* aff. *S. triquetra* (Gumbel) X160
20. *Astacolus* aff. *A. anceps* (Terquem) X142
21. *Hemirobulina woodi* (Bhalla and Abbas) X125
22. *Marginulina haynesi* Bhalla and Abbas X250
23. *Vaiginulinopsis* sp. indet. X132
24. *Citharina clathrata* (Terquem) X168
25. *Citharina hetroplura* (Terquem) X130
26: *Citharinella* aff. *C. compara* Loeblich and Tappan X165
27. *Epistomina hechti* Bartenstein, Bettenstaedt and Bolli X211
28. *Epistomina mosquensis* Uhlig X233
29. *Epistomina omninoreticulata* Espitalie and Sigal X158
30. *Epistomina* aff. *E. prerjasanesis* Pandey and Dave X235
31. *Epistomina regularis* Terquem X163
32. *Epistomina tenuicostata* Bartenstein and Brand X159
33. *Epistomina* sp. indet. X240

Plate -II

Plate III

(A) Photomicrograph showing Floating grains (F)

(B) Photomicrograph showing Point (P)and Long contacts (L)

(C) Photomicrograph showing Concavo-convex contacts (C-C)

Plate-III

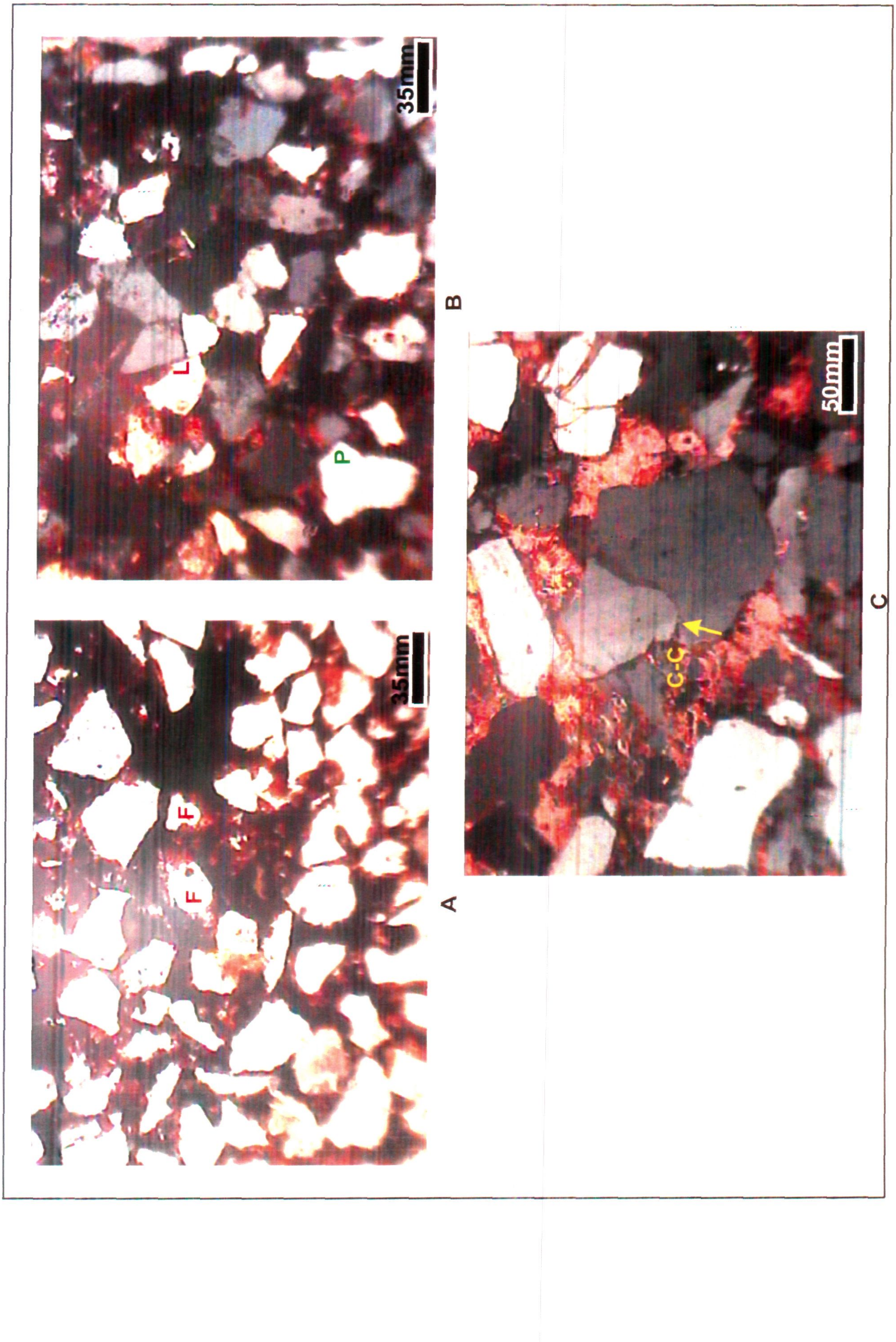


Plate IV

(A) Photomicrograph showing patchy distribution of calcite cement corroding feldspar and quartz grains

(B) Photomicrograph showing dark brown colour iron oxide cement corroding detrital grains and also replacing calcite cement indicating late stage cementation.

(C) Photomicrograph showing silica overgrowth around detrital grain.

Plate-IV

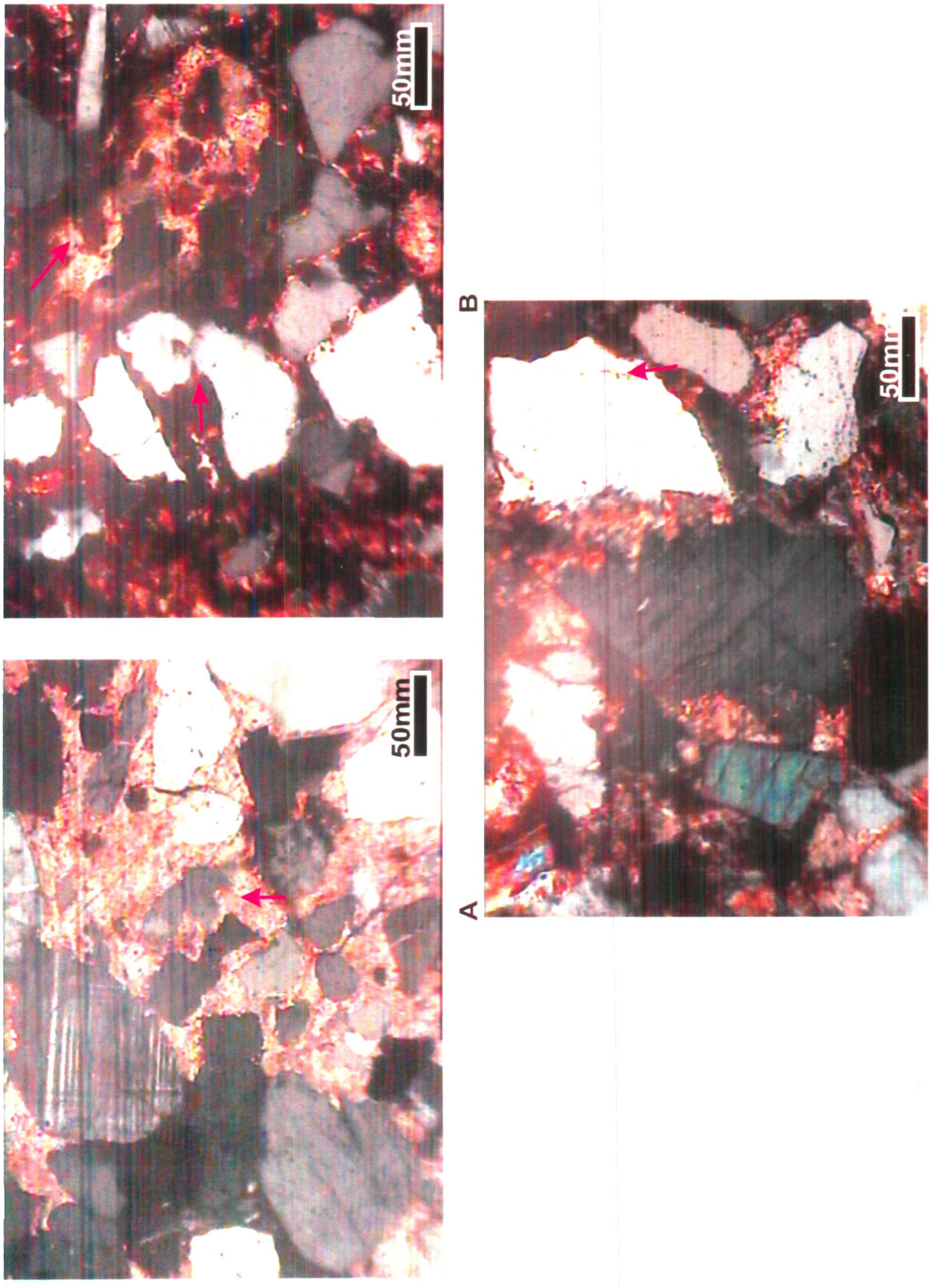
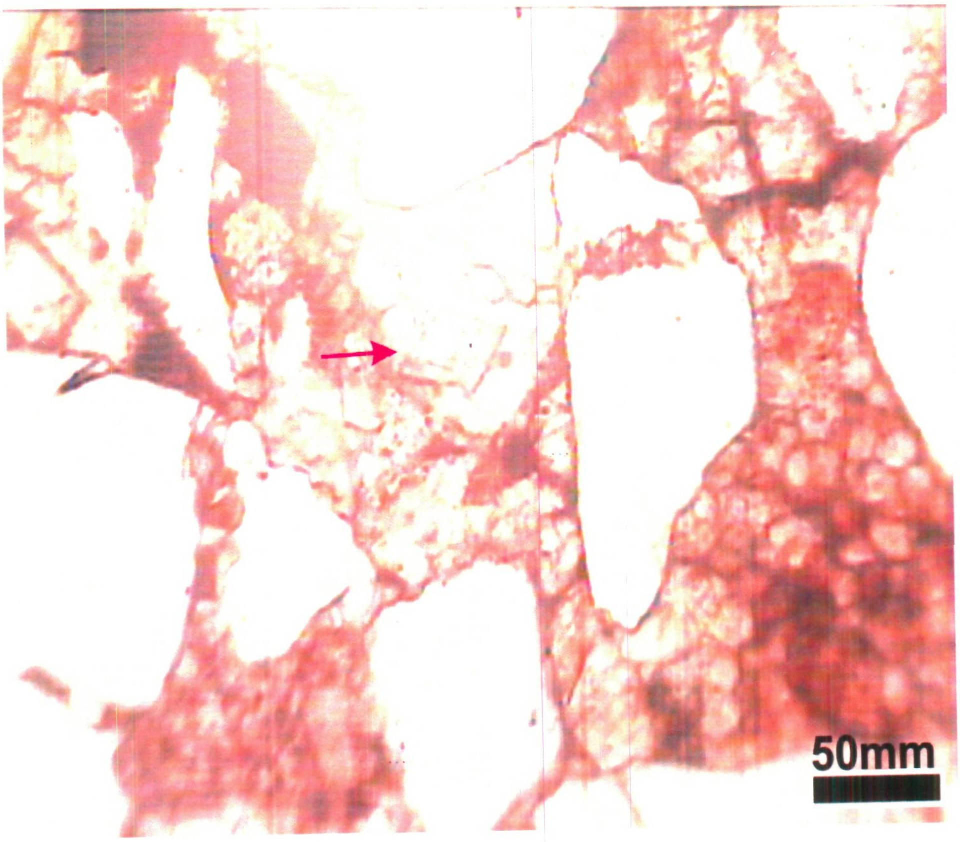


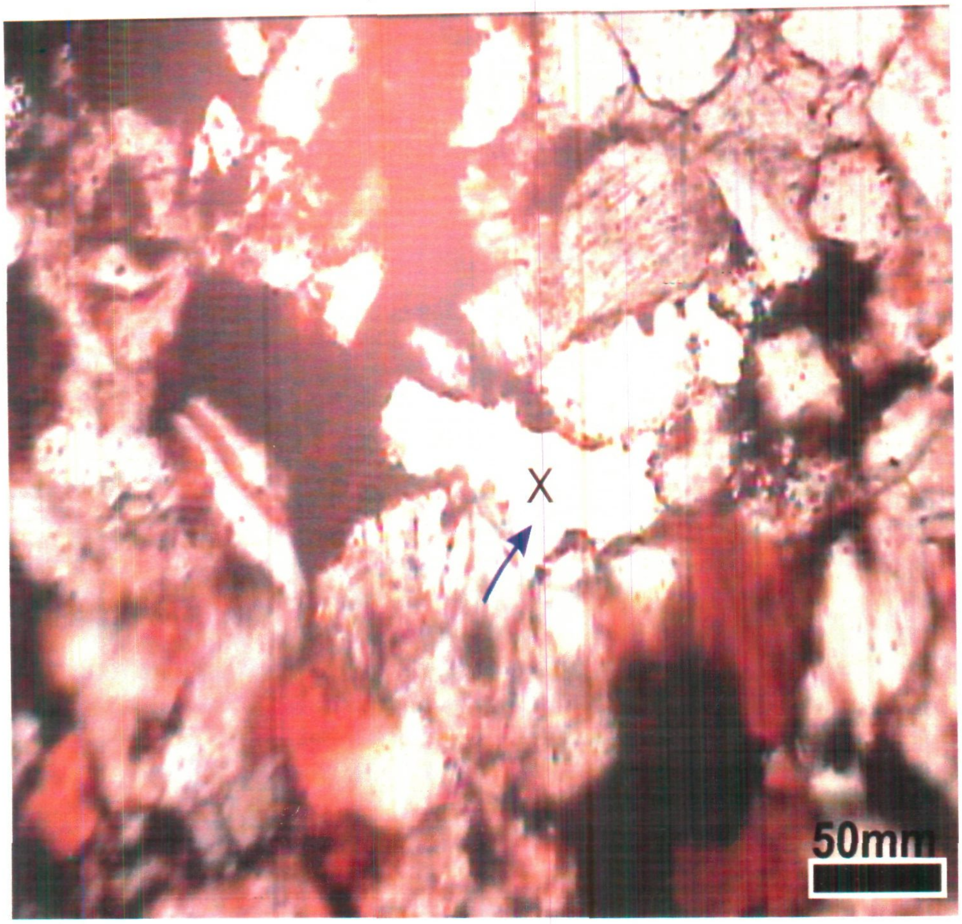
Plate V

(A) Photomicrograph showing dolometization of calcite cement.

(B) Photomicrograph showing secondary porosity developed due to iron and carbonate cement dissolution.



A



B